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A STUDY OF THE HYDRAULICS OF DENIL FISHWAYS

by

Ⓒ CHRISTOS KATOPODIS

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A STUDY OF THE HYDRAULICS OF DENIL FISHWAYS

MASTER OF SCIENCE

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Supervisor

Cl Rodkiewicz

Date 8 Sept 82

DEDICATED

To my loving wife
Shirley-Anne
for her endurance
and
To my sweet daughter
Christina
who arrived just as
writing began ...

Πάντα ρεῖ, εἶναι δέ παγίως οὐδέν
ΗΡΑΚΛΕΙΤΟΣ

Φύσιν μεταβαλεῖν οὐ ράδιον
ΕΜΠΕΔΟΚΛΗΣ

ABSTRACT

The development of Denil fishways is reviewed and the hydraulics of three Denil designs, referred to as Denil 1, 2 and 3, are studied experimentally and analytically. The very turbulent nature of the flow in the fishways is described and extensive velocity measuremets are presented. Velocity profiles in the centerline of Denil 1 and 2 are distinct and display characteristic shapes amenable to similarity analysis, while velocity profiles for Denil 3 are inconclusive in this respect. Depth averaged velocities through the fishways are found to be only 11% to 14% of the average velocities expected in rectangular channels of the same dimensions, indicating high efficiency in energy dissipation. A semi-empirical method is developed for the design of Denil fishways involving a fluid friction coefficient.

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LIST OF SYMBOLS

a - vane spacing
b - net width of fishway, chute or slot width
B - overall width of fishway, pool width
c_f - friction coefficient
d - depth of flow
$\bar{d}$ - adjusted depth of flow
E - specific energy for a fishway
E_o - specific energy for an equivalent rectangular flume
F - Froude number (based on depth averaged velocity)
F_o - Froude number for an equivalent rectangular flume
g - acceleration due to gravity
h - head drop per pool
k - baffle dimension, sill height
K - baffle dimension
L - pool length
m - suffix
M - constant dependent on the system of units
n - Manning's roughness for a fishway
n_o - Manning's roughness for an equivalent rectangular flume
Q - discharge
q - discharge per unit width for a fishway
q_o - discharge per unit width for an equivalent rectangular flume
R - hydraulic radius for a fishway
R_o - hydraulic radius for an equivalent rectangular flume
r - radius of current meter ring
R_b, R_p - current meter locations

S_o - bed slope of fishway

s - chute length

u - longitudinal velocity (time averaged)

u_m - maximum value of u

u'_m - velocity scale for Denil 2 fishway

V - "average" velocity in fishway

U - depth averaged velocity

V_o - mean velocity in an equivalent rectangular flume

x - longitudinal distance

Y - height of fishway

y - normal distance

y_o - depth of flow in an equivalent rectangular flume

z - transverse distance from centerline

γ - specific weight of water

ε - energy loss ratio: $1 - (E_o/E)$

η - aspect ratio: y_o/b

λ - depth ratio: y_o/d

ξ - roughness ratio: n_o/n

ρ - mass density of water

ϕ, ψ - baffle angles

τ_o - boundary shear stress

CHAPTER I

INTRODUCTION

Fishways are hydraulic structures that enable fish to overcome obstructions to their spawning or other migrations. These obstructions may be man-made, such as dams and other hydraulic structures, or natural, such as waterfalls and rapids. Blocking spawning migrations can seriously affect the fish resources of an entire river system. Should the blockage be complete and permanent, a species could be totally eliminated from the system. Fishways allow migratory fish to maintain access to their autochthonous habitat and are provided whenever social, ecological, economic or legal requirements exist.

Dams bring many problems for the maintenance of a stock of migratory fish. Building fishways is not a panacea for all the biological and physicochemical impacts on the watershed, that a dam produces. Fishways can only provide a migration path and thus assist fish either to reach traditional spawning areas or to colonize areas previously cut off by a barrier. Although most fishways were developed to serve the salmon, other migratory species have utilized them also. Fishways cannot be expected to maintain the same degree of access to migrating fish as a natural river would. Well designed fishways must always be regarded as aids to fish migrations and not as replacements for the natural migration paths.

In general, fishways are waterways which are navigable by fish moving upstream. Water flow within fishways is controlled so that fish are able to swim through the structure without undue stress. Flow control is achieved by employing devices which dissipate the energy of the water and maintain velocities within the biokinetic capabilities of migrating fish. A variety of energy dissipation schemes have been invented which give rise to a diversity of fishway types. Three basic fishway types are generally recognized: the pool and weir, the vertical slot, and the Denil.

The pool and weir fishway consists of a channel with regularly spaced weirs, each slightly higher than the one immediately downstream; thus a series of step-like pools are created. In this fishway, also known as the fish ladder, the weirs may incorporate orifices or short surface chutes. Water cascades over the weirs or flows through orifices and chutes into the pools setting up a circulation pattern around an axis perpendicular to the channel walls. Through this mechanism water energy is dissipated and velocities are controlled. Fish ascend from pool to pool by jumping or swimming over the weirs or by passing through the orifices or chutes. In the vertical slot fishway a series of pools is also created by the installation of baffles at regular intervals between the walls of the flume. Narrow slots, adjacent to either one or both walls, extend vertically over the full height of the baffle. Water flows through the slots creating small drops and disperses in the pools dissipating energy through circulation around an axis perpendicular to the flume floor.

The Denil fishway was first conceived by G. Denil in 1908. This is a flume equipped with closely spaced vanes (or fins, or baffles) on the sidewalls and floor. The vanes cause part of the flow to turn and oppose the main stream in the central part of the fishway. This arrangement provides considerable energy dissipation, establishes low velocity flow in the central zone of the fishway and allows fish a continuous and direct route of ascent. The intricacy of the original design led Denil and subsequent researchers to the development of simpler versions of this fishway. This study deals with three rather simple Denil fishway designs.

Physiological data on swimming modes and capabilities as well as behaviour of fish are very important in setting design criteria for fishways. Fish swimming speeds provide limits for the water velocities in a fishway and allow the designer to establish flow conditions that fish can navigate without undue delay or fatigue. Three levels of swimming activity are distinguished: the burst, prolonged and sustained speeds. The burst speed is a very high swimming speed which fish can maintain for less than 15 seconds. Energy for this activity is made available largely from anaerobic processes; consequently the fish fatigues rapidly and may be in a weakened condition afterwards. The sustained swimming speed comprises a spectrum of swimming activities that can be maintained for an indefinite period (longer than 200 minutes) and does not involve fatigue. Activities involved in this type of swimming include position holding, schooling, foraging and migration; metabolism is aerobic. Finally, prolonged speed represents the intermediate level of swimming performance and is often characterized by steady swimming with more vigorous efforts periodically. The swimming period ranges from 15 seconds to 200 minutes and if maintained will end in fatigue. Either or both aerobic and anaerobic processes supply the energy for these activities.

Swimming speeds vary with species and size of fish, time the effort is maintained, water temperature and other parameters. Generally the relationship between swimming speed and time, termed the fatigue curve, is curvilinear. Burst and prolonged speeds plotted against the logarithm of time usually result in straight lines for a given species and length of fish, provided other parameters remain the same. Equivalently, the water velocity that fish can swim against varies linearly with the logarithm of distance travelled. The slope of the fatigue curve is much steeper for the burst speeds than for the prolonged speeds. Such biokinetic relationships yield the maximum distance that a fish can travel against a given water velocity; this provides a meaningful constraint to the length of a Denil fishway. In the Denils a continuous swimming effort is required and fish use their burst or higher levels of their prolonged speeds to navigate the entire fishway length. The burst speed limits the maximum water velocities over weirs or through orifices, chutes and slots. Prolonged and sustained speeds set guidelines for providing areas where fish can rest within fishways or resting pools.

Probably the single most improtant factor in the success of a fishway is the location of the fish entrance (water outlet). If the entrance is not readily discovered by the migrating fish, they will be delayed for varying periods and, in the extreme case, may never enter the fishway. Hydraulic conditions and particularly water velocities within the fishway channel also determine the success and efficiency of the facility. Although a number of studies have been conducted, comprehensive data on velocity profiles in Denil fishways are lacking. The present study addresses this data deficiency for three Denil designs. The long term aims of this and, hopefully follow-up field and laboratory studies, are to arrive at effective, simple, practical and economical fishway designs and to develop a semi-empirical but general design method, so that the hydraulic characteristics of various designs can be predicted without reverting to direct testing.

CHAPTER II

LITERATURE REVIEW

HISTORICAL PERSPECTIVE

Annotated bibliographies on fishways have been published by Nemenyi (1941), The American Society of Civil Engineers (1960), and Brown (1976). Reviews on the development and design of fishways have been presented by the Committee on Fish-Passes (1942), McLeod and Nemenyi (1941), Rounsefell and Everhart (1953), Andrew and Geen (1960), Clay (1961), Ziemer (1962), Decker (1967), Eicher (1970), Bell (1973), Berg (1973), Jens (1973), Mahmood (1973), Larinier (1977), Hildebrand (1980), and Katopodis (1981). A long history of fishways has been recorded. Fishways were constructed in France at least as early as the 17th century. These fishways consisted of steep, broad, open channels, the bottoms of which were roughened with bundles of branches. Undoubtedly there were earlier attempts of even more primitive nature. However, it was the advent of hydraulic turbines, about the middle of the 19th century, and the consequent construction of high dams that induced the scientific investigation of fishways. Fishway design has since progressed from the crude, roughened channels into the three distinct types of Denil, vertical slot and pool and weir.

The design simplicity of the pool and weir fishway (Fig. 1) would suggest that this was probably the first to be developed. At the end of the 19th century Landmark was well known, at least in Norway, for building successful salmon ladders. Almost all of these ladders were intended to permit fish (Atlantic salmon, *Salmo salar*; Brown trout, *Salmo trutta* and Arctic charr, *Salvelinus alpinus*) to pass over natural falls in northern Norwegian rivers. A chain of pools, with a length of 3.0 - 4.0 m, a width of 2.5 - 3.0 m and a depth of 1.5 m, were usually created by blasting through rock formations. Often there were openings, 1.0 - 2.0 m in length and 0.6 - 1.0 m in width, between the pools. The slope of the ladders varied from 5% to 12.5% (Berg 1973). The design of the ladder has since been improved with the addition of orifices (Fig. 2) or chutes (Fig. 3). In the early 1960's these developments culminated in the Ice Harbor Dam design, on the Snake River, State of Washington, which is considered the most advanced (Fig. 2).

Landmark improved the traditional fish ladder (pool and weir fishway) by installing the weirs obliquely to one wall and extending across but not joining the opposite wall. Simple jet deflectors were placed on the opposite wall while the weirs remained perpendicular to the floor. Thus a narrow slot, extending the full height of the weir, was left along the one side of the fishway close to the wall (McLeod and Nemenyi, 1941). This fishway appears to be the forerunner of the vertical slot fishway (Fig. 4,5) which was developed in the 1940's under the guidance of M.C. Bell for use at Hell's Gate on the Fraser River in British Columbia (Fig. 4). Since the success at Hell's Gate the vertical slot has been used extensively.

The principle of operation of the Denil fishway probably originated with MacDonald at about 1879 in Virginia. MacDonald's invention consisted of a timber trough, 600 mm x 600 mm, with a slope as steep as 33.3%; in the trough 75 mm high cleats were laid at 300 mm centres along with two longitudinal boards 250 mm in height and 150 mm from the sides. Thus a 300 mm wide central path was left for the fish to pass (Committee on Fish-Passes 1942). This was the first attempt to redirect part of the flowing water in a fishway and turn it back to impinge on the main stream of flow and thereby dissipate the energy of the water.

Although early investigators made careful and extensive observations, no systematic scientific study of fishways appears to have been made until the beginning of the 20th century. The first fishway developed on scientific principles was probably that of G. Denil in Belgium. He presented his early design in 1908 and, over a period of 30 years, improved it, eventually devising the most effective energy dissipators known which do not involve moving parts. His latest publication appeared in the Annales des Travaux Publics de Belgique in 1936, 1937 and 1938. Nemenyi (1941) summarizes these articles which include attempts to understand the nautical properties and locomotion of fish, the resistances they encounter while swimming, extensive observations of fish navigating through fishways and hydraulic measurements on small scale models as well as actual fishways.

THE DEVELOPMENT OF DENIL FISHWAYS

White and Nemenyi (1942) and McLeod and Nemenyi (1941) conducted numerous laboratory experiments with small scale models of Denil type fishways. These experiments were seen as a means of easily and inexpensively checking a large number of old and new design variations and pave the way for the comprehensive study of larger models and prototypes. White and Nemenyi (1942) completed their investigations in 1938 on 25 different models at the Imperial College of Science and Technology, London, England, and consequently McLeod and Nemenyi (1941) tested another 15 models at the Iowa Institute of Hydraulic Research. Some of the most promising models from these investigations are shown in Fig. 6.

Model 1 in Fig. 6 is of historical interest. This is the original fishway developed by G. Denil in 1908. It was reproduced and retested by McLeod and Nemenyi (1941). Although this intricate design was found to be an efficient energy dissipator, it was substantially less so than some of the other simpler designs tested. Model 2 represents an attempt to apply the Denil principle of energy dissipation by using planar vanes of triangular and rectangular shape. This design was intended for construction either in timber or concrete, possibly in precast units. The results were very favorable. Energy dissipation was only slightly less than Model 4 which is essentially the same design except for the thin sheet metal vanes. Both Models 2 and 4 were recommended for prototype trials. Model 3 (Fig. 6) was built and tested as a prototype to Model 2.

Often a fishway must operate over a wide range of headwater levels. Since bottom vanes were expected to be hydraulically ineffective at large water depths, only the sidewall vanes could be relied upon to cause high energy dissipation. To accommodate such conditions, Denil (1938) eliminated the bottom baffles and designed a special pattern of planar, zigzag, herringbone vanes which were attached to the sidewalls of a rectangular channel. McLeod and Nemenyi (1941) simplified this design using plane, parallel metal plates or planks which were set at an angle to the channel sides and floor. Six alternative designs were tested of which Models 5, 6, and 7 (Fig. 6) proved successful in producing high energy dissipation. Models 5 and 6 were judged as superior and good energy dissipators respectively, while Model 7 gave results similar to Model 5. Full scale testing was not undertaken on these models, nevertheless they were recommended for field trial based on the favourable laboratory assessment.

Model 8 (Fig. 6) is another attempt by Denil to simplify his original design while maintaining high energy dissipation. White and Nemenyi (1942) tested this model under six slopes and at three flow depths and found it extremely steady hydraulically, relatively free of aeration, and the most efficient design for energy dissipation. White and Nemenyi (1942) do not give all the dimensions of the model they tested. The width of the clear opening (b) in the model (Fig. 6) was 101.5 mm and the vane spacing (a) was 3/8 of the overall channel width (B), i.e. $a = 0.375B$. For this design Denil (1938) gives $B = 2b$, so if White and Nemenyi (1942) proportioned their model accordingly, the overall width (B) should have been 203 mm and the vane spacing (a) 76 mm.

Model 3 led Ziemer (1962) in Alaska to the development and prototype testing of portable fishways, built from aluminum. He reported hydraulic measurements (depth and discharge) for two prototype versions which he named "Alaska Steeppass Model A and C". Model A is shown in Fig. 7 and Plates 1 and 2, with the following dimensions (in mm) given by Ziemer (1962): $b = 356$, $B = 556$, $k = 127$, $a = 254$, $Y = 686$. The vanes were perpendicular to the fishway floor and $\phi = 30°$. Model C had the same dimensions as Model A but $\phi = 45°$ and all the vanes lean upstream at 45° to the floor of the flume.

White and Nemenyi (1942) developed and tested the simplest Denil design to date. The advantage of this design over the previous ones lies in the construction simplicity of the vanes. Both the sidewall and bottom vanes have been incorporated into single-plane baffles (Fig. 8; Plate 3 and 4). Although White and Nemenyi (1942) provided a general description of the flow characteristics in this fishway, unfortunately neither the exact dimensions of the model tested nor the hydraulic measurements made were reported. The Committee on Fish Passes (1942) though, which commissioned the study, selected this design as the most practical and recommended the following dimensions for use in the field (Fig. 8; all dimensions in mm): $b = 533$, $B = 914$, $k = 152$, $a = (2/3)B = 610$, slope of 20%, and $\psi = 45°$. Recently, Larinier (1981) reported hydraulic measurements (depths and discharges) made in the laboratory with a simple Denil fishway of the following dimension (mm): $b = 175$, $B = 300$, $k = 70$. Table 1 summarizes the characteristic dimensions for a variety of Denil fishways.

The above investigators have taken an empirical approach in developing and testing Denil fishways. This approach has, very successfully, led to the evolution of simple, practical designs. Although some appreciation of the general flow characteristics has been gained, comprehensive research on velocity profiles and the energy dissipation mechanism has not been undertaken.

FIELD TESTING OF DENIL FISHWAYS

Designs by G. Denil

Nemenyi (1941), in summarizing Denil's investigations, reported that Denil undertook a number of field trials of his fishways and noted various degrees of success with salmonids (salmon and trout) and cyprinids (minnow or carp family). A number of early Denil designs were constructed in several locations in Europe and the USSR (Deelder 1958; Kipper and Mileiko 1967; Sakowicz and Zarnecki 1962). Most of these installations were unsuccessful. Fish entrance problems were reported in some of these structures, while several of them employed vanes only at the fishway floor and not on the sidewalls. All the fishways though were set at slopes ranging from about 30% to 60%. Such steep slopes were, probably, the main cause for failure.

Model 3 (Fig. 6)

McLeod and Nemenyi (1941), following their studies with models, carried out field tests on the Iowa River. Twelve different fishways were tested all of which were 7.3 m long and set at a slope of 25%. Among these were Model 3 (Fig. 6) and a larger Denil which was geometrically similar to Model 3 but 50% wider. For each test two fishways were operated simultaneously and the species, size and number of fish passing through each one were recorded. Over a period of 75 days, 15 such comparisons were made. Some fishway pairs were compared twice by reversing their position in the approach channel. It was found that fish did not favour one position over the other. Model 3 was used as an index to compare all fishways. The ratio of preference by fish for Model 3 over the other fishways ranged from 7:1, when compared with the pool and weir types, to 1.75:1 when compared with the larger Denil. All species of fish present used both Denil fishways and passed without injuries. It is noteworthy that a channel catfish weighing about 11 kg, measuring 838 mm in length and 229 mm across the head, passed through the clear opening of Model 3 which is only 254 mm wide.

The successful field trials with Model 3 led to the installation of similar fishways at five dam sites on the Des Moines River. These fishways were evaluated and the results were reported by Einer (1944) for the Lake Shetek fishway in Minnesota, and by Harrison (1948) and Harrison and Speaker (1950) for the fishways at Fort Dodge, Humboldt, Rutland and Des Moines in Iowa. Einer (1944) concluded that the fishway at Lake Shetek was entirely successful for the fish species in the Des Moines River except for the Centrarchids (sunfish family). From April 1 to October 24, 1943, and from April 1 to October 15, 1944, the fishway was kept under constant observation. The largest fish to ascend the fishway was a northern pike (Esox lucius) 620 mm long, weighing 2.3 kg, while white suckers (Catostomus commersoni) as small as 100 mm in length were able to pass.

Harrison (1948) along with Harrison and Speaker (1950) provided four years of data (1946-1949) on the species, numbers and sizes of fish that passed through the fishways at Humboldt and Rutland, three years of data (1947-1949) for the fishway at Fort Dodge, and one year (1948) of such data for the fishway at Des Moines. All fishways were set at a slope of 25%, except for one of the two sections at Humboldt which was set at a slope of 16.67%. The length of the fishway sections ranged from 5.5 m to 8.2 m. All species of fish which attain a total length of 152 mm or more in life, except for the northern hog sucker (Hypentelium nigricans), living in the areas of the fishways made use of them. The fishways were apparently non-selective with respect to species and size in that they passed fish in relative numbers to their size and abundance in the river. The fish species that utilized the fishways on the Iowa River, Lake Shetek and on the Des Moines River included primarily Catostomids, Cyprinids and Ictalurids. Small numbers of northern pike (Esox lucius) and walleye (Stizostedion vitreum) were involved.

The Steeppass (Fig. 7)

Ziemer (1962) reported several successful installations of the steeppass in Alaska, ranging from 6.1 m to 27.4 m in length and set at slopes of 26.2% to 19.7%. All Pacific salmons present (Oncorhynchus spp.), including pink (O. gorbuscha), chum (O. keta), coho (O. kisutch), and sockeye (O. nerka), passed through the fishways. Ziemer (1962) estimated that the steeppass had a capacity of 750 fish per hour.

Thompson and Gauley (1964) experimented with a 6.1 m long steeppass on a 33% slope at the John Day Dam on the Columbia River. Coho (O. kisutch) 305-914 mm in length, chinook (O. tshawytscha) 356-1219 mm in length, and steelhead trout (Salmo gairdneri) 457-1016 mm in length, used the fishway. There was no evidence that any fish, even the largest individuals, rejected the fishway. Results from fish counts for twelve tests were recorded. The highest mean count was 410 fish per hour, while the maximum count was 2520 fish per hour with no evidence that peak passage had been reached. Weaver et al (1976) tested a 9.1 m long steeppass in 1968 at the Fisheries-Engineering Research Laboratory located at Bonneville Dam also on the Columbia River. The laboratory is located adjacent to the Washington shore fish ladder. Fish can be diverted from the ladder, observed as they pass on their own volition through experimental conditions in the laboratory, and allowed to reenter the ladder continuing their migration. Sockeye, chinook and steelhead successfully passed at slopes of 27% and 40%. These fish ranged in length (mm) from 300-580 for sockeye, 300-1050 for chinook, and 350-800 for steelhead.

Slatic (1975) also conducted a number of evaluations on the steeppass at the above laboratory. Steeppass sections 7.9 m, 9.1 m and 15.2 m long were tested at 24%, 28.7% and 28.7% slopes, respectively. Fish species that successfully negotiated these Denil fishways included the various Pacific salmons, as well as, American shad (Alosa sapidissima), suckers (Catostomus spp.), northern squawfish (Ptychocheilus oregonensis),and Pacific lamprey (Entosphenus tridentatus). Slatic (1975) estimated that the fish passage capacity of the fishways would most likely fall within a range of 650 to 1140 fish per hour.

Extending the 9.1 m long fishway to 15.2 m, while maintaining the slope at 28.7%, had no adverse effect on passage efficiency. When offered a simultaneous choice between a Denil fishway (i.e. a steeppass) and a pool and weir fishway, the majority of the fish chose the Denil. Approximately 95% of all the salmonids selected the Denil and only 5% chose the pool and weir. None of the American shad entered the pool and weir fishway, while 32% of them entered and passed through the Denil fishway in the one hour tests. As a result of these tests two Denils were installed at the Little Goose Dam on the Snake River and had been used successfully for three years. They passed fish without any apparent injuries or noticeable delay.

Tack and Fisher (1977) carried out field tests in Poplar Grove Creek, Alaska, with a 6.1 m long steeppass. Tests were performed with the fishway set at 7.5%, 11.25% and 15.0% slope and for discharges of 49-127 L/s. Arctic grayling (Thymallus arcticus), longnose sucker (Catostomus catostomus) and rainbow trout (Salmo gairdneri) were involved. It was found that the fishway was fully accepted by the migrating fish of the Poplar Grove Creek. All fish showed a success rate of 80% or better except for the yearling grayling (85-130 mm in length) which showed an overall success rate of 33%. Adult grayling achieved the best success rates (near 100%) at a slope of 15.0% and a discharge of 127 L/s which was the most difficult condition tested. Juvenile grayling (130 mm-maturity) also did best (92% success rate) at the highest slope and discharge tested. Yearling grayling, however, reached their best success rate of 44% at a slope of 11.25% and a discharge of 82 L/s, and they were severely inhibited at a slope of 15.0% and higher discharges.

The Denil fishway (Fig. 8)

Clay (1961) reported that Denil fishways (Fig. 8), based on the design recommended by the Committee on Fish-Passes (1942), had been used in several European countries. At least three fishways were reported in Sweden, including one at the Herting power dam. These fishways had successfully passed salmon, sea trout, and brown trout down to extremely small sizes. The smallest size reported at normal fishway flows was a brown trout weighing 180 g. However, at a flow of 8.5 L/s, which is about 1% of normal, roach and perch as small as 50 mm in length were reported to have ascended (Clay 1961). The apparent success of the fishway at Herting Dam, generated interest for this design in North America. A Denil fishway was installed at Dryden Dam on the Wenatchee River, a tributary to the Columbia River. This Denil fishway was located side by side with a pool and weir fishway. Observations on the two fishways were reported by Fulton et al (1953).

Fulton et al (1953) provided the dimensions of the fishway at Herting. The channel width (B) was 1300 mm and the width of the clear opening (b) 760 mm, representing an increase of approximately 42% over the dimensions recommended by the Committee on Fish-Passes (1942). The fishway slope was decreased to 16.67%, the angle between the vanes and the floor was maintained at 45°, and the vane spacing was kept at 2/3 of the channel width. The longest section between resting pools was 9.02 m. The Denil fishway at Dryden Dam was patterned after the Herting installation and had the following dimensions (mm): b = 762, B = 1302, a = 864, k = 292, Y = 1768-2134. The fishway was 8.6 m long and on a 16.67% slope. Sockeye and chinook salmon, steelhead trout, Dolly Varden (Salvelinus malma), suckers (Catostomus spp.) and northern squawfish (Ptychocheilus oregonensis) used the fishway. Based on two years of observations, 89% of the fish used the Denil fishway and 11% the pool and weir. It was concluded that the foremost advantage of the Denil was the attractive entrance conditions created by the nature of the fishway outflow. The Denil also proved superior in facilitating fish passage. Fish appeared to arrive at the fishway exit with little effort. The short time required for a salmon to negotiate the Denil never failed to startle the observers and was in contrast to the tardy progress through the pool and weir. During short periods of observation, fish passed through the Denil at an average of 24 s intervals. On numerous occasions several sockeyes passed through simultaneously or in rapid succession.

The capacity of a fishway to transport sediments could affect the maintenance of the facility, particularly in streams which carry large quantities of bedload. Field tests with the Denil fishway at Dryden Dam were reported by Cagle (1953). Gravels and cobbles were dumped into the fishway at the inlet and their movements observed. A counter flow at the bottom of the fishway seemed to push the gravel into the main flow. The gravel moved through the fishway by saltations from one vane to the next. It was concluded that the fishway would not retain any sediment particles 100 mm or smaller. The largest cobble tested, measuring 356 mm x 178 mm x 178 mm, moved six vane spacings or a distance of 5.2 m in 20 minutes.

Since the successful testing at Dryden Dam, the Denil fishway has been widely used both in the Pacific and Atlantic coasts of North America. Decker (1967) reported that in the state of Maine Denil fishways up to 227 m in length (including resting pools) have been built and hydraulic heads of up to 15 m have been accommodated. Channel widths have varied from 600 mm to 1200 mm and in all cases, the designs were geometrically similar to the one recommended by the Committee on Fish-Passes (1942). Most fishways were built on a 16.67% slope, although a few were installed on a 12.5% slope. The vanes were sloped 3 vertical to 2 horizontal making the angle between them and the floor (ψ) approximately 47° and 49° for the 16.67% and 12.5% slopes, respectively. Winn and Richkus (1972) evaluated the passage of alewife (Alosa pseudoharengus) through two Denils on the Annaquatucket River, Rhode Island. DiCarlo (1975) described several Denils installed in Massachusetts. Boreman (1981) reported on the successful utilization by rainbow trout (Salmo gairdneri) of a Denil fishway on the Cayuga Inlet, New York. The dimensions of this fishway, as provided by Webster and Otis (1973), were: slope 12.5%, length 13.0 m, b = 610 mm, B = 1067 mm, a = 648 mm, and the vanes were sloped at 3 vertical to 2 horizontal.

CHAPTER III

EXPERIMENTAL ARRANGEMENTS

APPARATUS

Three Denil fishway designs were studied at the T. Blench Hydraulics Laboratory of the University of Alberta. For convenience these designs were referred to as Denil 1, 2, and 3. All three were full scale models, so no scale effects were involved in this study. Denil 1 was the steeppass (Fig. 7, Plates 1 and 2) with the dimensions given by Ziemer (1962). Denils 2 and 3 retained the features of the simple Denil design of Fig. 8. (Plates 3 and 4). The dimensions for the three fishways are shown in Figs. 9 and 10. Denil 2 had the same dimensions and vane spacing as Denil 1. Denil 3 was identical to Denil 2 except for the vane spacing which was set at approximately (2/3)B as was recommended by the Committee on Fish-Passes (1942).

The experiments were conducted in the arrangement shown in Plate 5. A steel framed flume with 13 mm thick plexiglass sidewalls was constructed. The flume measured 4.9 m (16.0 ft) in length, 560 mm (22") in width and 690 mm (27") in height (Fig. 9). The vanes for each fishway design were prefabricated using 16 gauge (1.6 mm) galvanized sheet metal. Subsequently, the vanes were fitted in the flume, supported at the bottom and sides and sealed to prevent water leakage.

A headtank, equipped with stilling arrangements, was attached to the flume inlet. The stilling arrangements consisted of a series of circular pipe sections (152 mm in diameter and 914 mm in length) followed by a double screen (16 gauge or 1.6 mm, galvanized wire mesh) with a 51 mm thick layer of "hogs hair" in between. The headtank and flume assembly was supported by a cement block on the upstream end. A hinge allowed the upstream end to rotate while the downstream end could be lifted by a crane, set at a desired slope, and then supported.

Water was circulated through the system by pumping from the laboratory sump through an overhead pipeline (305 mm in diameter) leading to the headtank. From the headtank, water entered the flume through the stilling arrangements, flowed through the fishway, and spilled back into the sump.

HYDROMETRIC TECHNIQUES

The water discharge through the fishway was measured by a magnetic flow meter installed in the pipeline. For the water surface profiles, a point gauge with a least count of 0.3 mm (0.001 ft) was used. The velocity readings were obtained using a current meter having an external ring diameter of 15 mm (Plate 6). For all the experiments on Denil 1 and for one-third of the experiments on Denil 2 (third slope), the reading on the current meter dial was visually averaged, whereas for the remaining experiments, the output from the current meter was connected to a paper tape from which an average for each reading was obtained. Fig. 11 shows a sample output of the paper tape; numbers 56-1 to 56-15 refer to readings taken at different points along a central plane, starting at the bottom and moving towards the surface. Some observations were made on the flow patterns and the extent of air entrainment in the flow.

Although the limitations of resources and time for the study did not allow for a detailed evaluation of these factors, significant errors in the velocity measurements may have been introduced by air entrainment flow meter alignment and flow turbulence. Considering the size of the current meter, large air bubbles could, conceivably, have encased the probe from time to time thereby producing lower velocity readings. It was anticipated though that the extended time of observation for visual (60-90 s) or recorded (50 s per inch, Fig. 11) readings would minimize the air entrainment effect on average velocities. Since the current meter axis was always set parallel to the longitudinal axis of the fishway, only the corresponding directional component of the velocity was measured. The magnitude of the velocity in the direction of flow at a particular point would actually be greater. This angularity effect was suspected to be negligible along the centerline but more pronounced near the vanes and walls of the fishway. Also unknown is the effect on the current meter readings of the very turbulent nature of the flow.

PRELIMINARY OBSERVATIONS

Range of Experimental Parameters

Considering the results of previous investigations, it was initially decided to test the fishways for three slopes of approximately 10, 20 and 30% and three discharges for each slope. As a result, the final values of the three slopes tested were 10.0%, 20.1% and 31.5%. Each slope was tested for three discharges of 56.6 L/s (2 cfs), 85.0 L/s (3 cfs) and 113.3 L/s (4 cfs). A total of 27 experiments (9 for each fishway) were conducted. A coding system was used to identify the different experiments and the associated velocity profiles. A test code was devised in which the first number refers to the type of fishway, which could be 1, 2 or 3 corresponding to Denil 1, Denil 2 or Denil 3, respectively. The second element of the could be A, B or C denoting, respectively, the slopes of 10.0%, 20.1% and 31.5%. The third element, a number, could be 2, 3 or 4 corresponding to the discharge tested in cfs. The last element of the code (if present) is a compound one which could be CL, denoting centerline, L3, denoting 3" on the left of the central plane of the fishway looking upstream, or R5 which represents a transverse distance of 5" to the right of the central plane, etc.

Rationale for Selecting Test Sections

From visual observations it was recognized that there was a flow development length of about 60-80 cm in the initial part of the fishway where the flow accelerated and towards the end of the fishway there was an exit length of about 60-80 cm in which the flow was affected by the free overfall at the end. In between the inlet and outlet affected reaches, there was a region of fully developed flow in which the water surface profile in the central plane of the fishway was approximately parallel to the bed of the channel (Fig. 12). From velocity observations along the centerline it was found that the velocity profiles were essentially invariant in the region of fully developed flow (Fig. 13a-r). Accordingly the testing stations for velocity measurements for the three fishways were selected as indicated below (all distances measured from the fishway water inlet):

Denil 1 - Station 1: 188 cm (6'2")
Station 2: 201 cm (6'7")
Station 3: 213 cm (7'0")
Denil 2 - Station 1: 201 cm (6'7")
Station 2: 213 cm (7'0")
Station 3: 226 cm (7'5")
Denil 3 - Station 2: 213 cm (7'0")

CHAPTER IV

EXPERIMENTAL RESULTS

GENERAL FLOW OBSERVATIONS

The flow in the three fishways tested consisted of two interacting parts: a main stream in the central portion of the channel and a series of systematic lateral streams, each one corresponding to a side pocket created by the vanes. Observations revealed the very turbulent nature of the flow. Very extensive mixing was evident between the predominantly unidirectional main stream and the ever swirling, lateral streams. Water was directed by the vanes into the side pockets, where large circulation patterns were set up; subsequently, water was redirected to strike and to counteract the main stream. Considerable air entrainment was noted throughout the flow. The motions of air bubbles provided a visual appreciation of the nature of the flow in the fishways (Plates 7-38).

The main stream, although idiomorphic, was characterized by symmetry, strong surface undulations, and sizable, systematic and periodic water level fluctuations. The lateral streams were symmetric, homologous and isodynamic when compared to one another. Each lateral stream displayed large scale spiral motions and rythmic water level oscillations, while all together synchronically and synergistically counteracted the main stream. The strength of the lateral steams appeared to be proportional to the vigor of the main stream. The intense and vigorous interaction between the main stream and the lateral ones appeared to provide the main mechanism for transferring mass and momentum, and producing considerable turbulence and energy loss (Plates 7-38).

Closer examination revealed both the similarities and the differences in flow conditions in each fishway. For a discharge of 113.3 L/s and for each of the three slopes tested, Plates 7-9, 17-19, and 28-30 purvey a view from the top for the flow patterns exhibited by Denil 1, 2, and 3, respectively. Denil 1 displayed strong lateral streams which striked the main stream almost perpendicularly. At the 31.5% slope each lateral stream extended to the centerline of the channel and collided with the corresponding stream from the opposite side of the fishway. Water level in the side pockets rised significantly higher than in the central plane of the fishway. As slope was decreased, the lateral streams became weaker, the water level differences between the side pockets and the main channel diminished, and flow turbulence decreased. In contrast to Denil 1, Denil 2 (Plates 17-19) and Denil 3 (Plates 28-30) exhibited a smoother, yet faster moving water surface. The lateral streams were less conspicuous and appeared to involve spiral motions around an axis parallel to the wall vanes. For Denil 2 and 3 the interaction between the main stream and the lateral streams was not as intense as in Denil 1. Flow turbulence decreased with slope, although not to the same degree as in Denil 1. Denil 2 displayed less turbulence than Denil 3. The increased spacing of the vanes in Denil 3 appeared to render the lateral streams less effective in slowing down the main stream than in Denil 2.

When viewed from the side, Denil 1 manifested large scale circulation patterns. Each lateral stream consisted essentially of flow moving in a spiral path around an axis perpendicular to the wall vanes. Turbulence and air entrainment were high but both decreased with slope and discharge. Sizable water level differences from one wall vane edge to the next were noted (Plates 10-12). Side views of Denil 2 (Plates 20-22) and Denil 3 (Plates 31-34), disclosed higher air entrainment than in Denil 1 for the same slope and discharge and confirmed a high velocity stream in the upper layer of the flow. Wave patterns, with a wave length approximating the vane spacing, were featured at the water surface of both Denil 2 and 3. Pockets of slower moving water were evident close to the floor of the fishways.

Close-up photographs showed how the nature of the lateral streams changed with slope and discharge (Plates 13-16 for Denil 1, 23-27 for Denil 2, and 35-38 for Denil 3). For Denil 2 and 3 flow observations indicated that, in descending from the water surface towards the fishway floor, the direction of flow circulations shifted. Close to the water surface the main stream moved more or less parallel to the floor. This direction gradually changed to produce an almost vertically upward motion near the bottom of the flume. As noted earlier , the lateral streams displayed a spiral motion near the surface around an axis parallel to the vanes. This motion changed to a downward one at mid-depth and to an inward one near the bottom. The inward motion contributed to the upward movements which were displayed by the main stream. Evidence of these flow patterns is provided by Plates 21-22 and 26-27 for Denil 2, as well as Plates 32-34 and 37-38 for Denil 3. Similar flow characteristics were described by Fulton et al. (1953) and Larinier (1981). The upward motions near the floor also concurred with observations by Cagle (1953) on the movements of gravel deposited in the Dryden Dam fishway.

VELOCITY PROFILES

The nature of the velocity field in each fishway was studied by measuring the distribution and magnitude of the velocity u (time averaged) in the direction of the centerline of the fishway. This velocity was measured in the region of developed flow at several points along the central normal (or in the central plane) and a number of non-central normals. The range of velocity fluctuations were recorded also.

Denil 1 Fishway

The variation of u with y in the central normal is shown in Fig. 14, for the nine experiments with the Denil 1 fishway. In the plots of Fig. 14 the vertical axis (depth) corresponds to y as defined in Fig. 9 and the horizonal axis (velocity) corresponds to the time averaged velocity readings made at the centerline of the fishway. In most of the experiments, the velocity profiles at the three stations exhibit similar characteristics. They all display the same geometrical shape. The maximum velocity u_m, occurs at $y=0$; u decreases with y, reaching a minimum value somewhere below the free surface. In Fig. 14 the water surface is represented by the straight horizonal lines across the plots (solid, dashed or dotted lines). These velocity profiles vary little from station to station for the same slope and discharge. The only exception is station 1 for experiment 1B3CL (Fig. 14e) which was attributed to experimental error.

Velocity profiles were also established at a number of non-central normals and are included in Appendix 1 (Fig. 1.1). For these velocity profiles the following characteristics can be observed: a) they are generally symmetrical on either side of the central plane; b) the profiles for L3, R3, L5 and R5 (i.e. 76 and 127 mm from the central plane) have nearly the same geometric shape as the centerline profiles; c) the u values tend to remain approximately the same for different values of y for the profiles for L7, R7, L9 and R9 (i.e. 178 and 229 mm from the central plane and inside the side pockets). When moving transversely away from the central plane, the typical shape of the centerline velocity profiles appears to shift gradually to a nearly vertical line of constant velocity. The magnitude of the velocities also appears to be decreasing in the same direction.

Denil 2 Fishway

The centerline velocity profiles for the nine experiments with the Denil 2 fishway are shown in Fig. 15. These profiles are characterized by low and approximately constant velocities up to a certain depth, with a gradual increase in magnitude thereafter, reaching maximum velocities at the free surface. This is consistent with the observed fast water layer near the free surface which was described previously. The geometric shape of the profiles is generally the same and a mean curve could easily be drawn for the two or three stations of each experiment. Velocity profiles for the non-central normals (Appendix 1, Fig. 1.2 for L3, R3, L5 and R5) exhibit trends similar to the centerline profiles. Velocity measurements in the side pockets were not made as the inclined vanes rendered this task impractical.

Denil 3 Fishway

As was discussed previously, flow observations in the Denil 3 fishway indicated that the vanes were not as effective in slowing the main stream as in the case of Denil 2, because of the increased spacing. The centerline velocity profiles, shown in Fig. 16, support these observations. Further, they indicate that even though the profiles for the 10.0% slope appear to have the same shape as that in Denil 2, the profiles for the other two slopes suggest an almost uniform velocity. By combining the centerline profiles for each slope (Fig. 16j to 16l) it is interesting to note that for a slope of 10.0%, the velocity profiles do not seem to be affected by the discharge. This trend though does not necessarily persist for the 20.1% and 31.5% slopes. For Denil 3, centerline velocity measurements were made only at station 2, and the noncentral velocity profiles (Appendix 1, Fig. 1.3) were also limited.

VELOCITY CONTOURS

Velocity contours were drawn from the time averaged velocity measurements made at the different normals. These contours shown in Fig. 17 for Denil 1, Fig. 18 for Denil 2 and Fig. 19 for Denil 3, provide a more comprehensive view of the velocity field on the three fishways tested. In these plots, the vertical axis (depth) corresponds to y as defined in Fig. 9; the horizontal axis (width) corresponds to the transverse distance from the centerline (taken as 0) and extends to the furthest point where velocity readings were made on either side of the central plane. A mean water surface level is marked and the velocities are specified in cm/s for contour intervals of 10 cm/s. The velocity contours for station 2 are the most comprehensive for each fishway. The limited data for Denil 3 allowed only one graph to be plotted (Fig. 19).

The shape and distribution of the isotachs confirm some of the observations which have already been made. Flow is generally symmetrical around the centerline and particularly so for Denil 1. For the Denil 1 fishway (Fig. 17) high velocities exist at the bottom layers of the flow. The close spacing of the isotachs indicates that velocities reduce rapidly reaching a minimum at approximately 60% of the flow depth. Also, velocities appear to diminish with distance from the centerline. Sharp turns in the isotachs are usually noted at some distance on either side of the centerline. These represent the influence of the sidewall vanes of the fishway. The interior edges of the vanes were approximately 18 cm from the centerline.

In the Denil 2 fishway (Fig. 18) the isotachs, in the clear opening of the channel, when compared to those for the Denil 1 display a different pattern for the velocity field. Consistent with previous observations, high velocities are exhibited close to the water surface which subsequently are reduced considerably in the bottom layers of the flow. The isotachs for Denil 2 are generally not as closely spaced as the ones for Denil 1, indicating a more gradual change in velocities. In a similar way to the Denil 1 fishway, velocities in Denil 2 are reduced with distance from the centerline, although this reduction appears to be more gradual. The velocity contours of the only plot available for Denil 3 (Fig. 19) exhibit characteristics similar to those for Denil 2.

CHAPTER V

ANALYSIS

FLOW DEVELOPMENT

The longitudinal water surface profiles of Fig. 12 illustrate the three flow development regions observed. Immediately after the stilling arrangements of the headtank, flow was typical of a rectangular open channel on a steep slope: uniform, with low water depth and high velocities. Within the short distance between the end of the stilling arrangements and the uppermost fishway baffle, flow depth increased steadily. Water depth continued to increase, for approximately 60-80 cm into the fishway, until a depth was reached which was maintained for almost the entire fishway length. Only for approximately 60-80 cm at the downstream end of the fishway did the water depth decrease under the influence of the free overfall arrangement. For all the experiments conducted with the three fishways, a flow development region was observed, followed by a fully developed flow region and a drawdown section at the water outlet. The fully developed flow region was characterized by longitudinal water surface profiles, in the central plane of the fishway, which were approximately parallel to the bed of the channel (Fig. 12).

In an actual field installation, an initial flow development region is unlikely since the water inlet (or the fish exit) of the fishway is placed in a relatively calm area of a reservoir or a lake upstream of an obstruction. In the field then, fully developed flow is expected to begin in the immediate vicinity of the uppermost baffle. In this respect, the initial flow development region observed in the laboratory was not expected to represent field conditions. Also in most situations, the free outfall of the laboratory experiments would not correspond to an actual field setting. In the field, the water outlet (or fish entrance) would be influenced by the elevation of the tailwater. Normally, there would not be a significant drop in water level between the water outlet and the tailwater. Apart from the short inlet and outlet region, the fully developed flow region is expected to represent field conditions reasonably well.

Velocity profiles for Denil 1 and 2 are shown in Fig. 13a to f and 13g to r, respectively, for different central normals along the length of the flume. For experiment 1B2, the velocity profile at 61 cm from the water inlet (Fig. 13a) deviates substantially, while the velocity profile at 127 cm deviates only slightly from the remaining velocity profiles. This testifies to the presence and influence of the flow development region. The velocity profiles of Fig. 13b and c appear similar to each other as well as to the corresponding centerline profile of Fig. 14d in which stations 1, 2, 3 were, respectively, 188, 201 and 213 cm from the water inlet. A small deviation from these profiles is detected in Fig. 13d, which represents velocity profiles influenced by the free outfall. The water outlet was 488 cm downstream of the inlet. Fig. 13e and f along with Fig. 14h provide further evidence that the flow was relatively steady and uniform in the fully developed flow region. Fig. 13g to r in conjunction with Fig. 15a, d and g, offer evidence similar to the above regarding the three flow regions observed in Denil 2.

SIMILARITY ANALYSIS

In the presentation of the experimental results it was pointed out that the velocity profiles for Denil 1 and 2 exhibited, generally, similar geometrical shapes. Mathematically, velocity profiles are termed "similar" if the dimensionless local velocities plotted against the dimensionless local depths fall on one common curve. The velocities and depths are non-dimensionalized by appropriate velocity and length scales. These scales characterize the flow and assist in its description and analysis. Similarity of the velocity profiles is a property manifested by a very large number of turbulent jet flows. The maximum velocity of the profile is commonly used as the velocity scale (Rajaratnam 1976).

For the Denil 1 centerline velocity profiles (Fig. 14) the similarity hypothesis was tested by chosing u_m, the maximum value of u occurring at y=0 (Table 2), as the velocity scale, and d, the depth of flow, as the length scale. The dimensionless local velocity (u/u_m) was then plotted against the dimensionless local depth (y/d). From Fig. 20 it is found that almost all the experimental points cluster around a common curve, attesting to the validity of the similarity hypothesis for the centerline velocity profiles of the Denil 1 fishway. The hand drawn curve of Fig. 20 is characterized by (a) a high velocity region near the bottom, where $u/u_m \approx 1.0$ for $y/d \approx 0$, (b) a section in which velocities reduce rapidly to $u/u_m \approx 0.4$ for $y/d \approx 0.55$, and (e) an area in which velocities change very gradually, reaching a minimum $u/u_m \approx 0.32$ for $y/d \approx 0.77$.

The similarity hypothesis was also tested with the centerline velocity profiles for Denil 2 by plotting u/u'_m versus y/d (Fig. 21). Here, the velocity scale, u'_m (Table 2), represents the velocity of the profile at $y=0.75d$. The selection of this velocity scale was necessitated by the nature of the centerline profiles for the Denil 2 fishway (Fig. 15). In contrast to the profiles for Denil 1 (Fig. 14), where a maximum velocity (u_m) could be easily defined near the bottom, the maximum velocity for the Denil 2 profiles appeared to occur at or near the water surface. The experimental technique adopted for this study could not have been used to accurately measure velocities very close to the water surface because the flow oscillations there caused the current meter to be alternately submerged and exposed. If the results of experiment 2A4, which appeared to be very different (perhaps due to measurement problems), are omitted, then a mean curve could be drawn through the data points of the remaining experiments. This curve indicates that the velocity in the lower layers is approximately constant at $0.65u'_m$ for y to about 0.3d and then increases continuously to reach a value of about $2.7u'_m$ near the free surface (extrapolated value, not shown in Fig. 21).

VELOCITY SCALES

The similarity profiles presented above can be used to predict the mean velocity field in the fishways if the velocity scales (u_m,u'_m) can easily be estimated from other known flow parameters. A convenient and practical such parameter, which has been used by previous investigators to characterize flows in Denil fishways, is the "average" velocity (V) computed from the discharge-area relationship assuming steady, uniform flow. This velocity is defined as the ratio of fishway discharge to the net flow area which is bounded by the vane edges and is normal to the flume floor (McLeod and Nemenyi 1941; Smith 1976; White and Nemenyi 1942; Ziemer 1962). The net flow area would be bd for Denil 1 and $b\bar{d}$ for Denil 2 and 3 (Fig. 9). This "average" velocity is then given by:

$$V = \frac{Q}{bd} \quad \text{(Denil 1)} \qquad \text{or } V = \frac{Q}{b\bar{d}} \quad \text{(Denil 2, 3)} \qquad (1)$$

The velocity V from (1) is tabulated in Table 2, along with the ratios u_m/V for Denil 1 and 3, and u'_m/V for Denil 2. These ratios were plotted against d/b in an attempt to arrive at a method of predicting the velocity scales (u_m and u'_m). From Fig. 22 it is found that for Denil 1 u_m/V increases with d/b for all three slopes and the full range of discharges tested. For Denil 2, $u'_m/V \approx 0.5$, whereas for Denil 3, u_m/V increases in d/b. It is noted though that significant scatter is displayed by the data of Fig. 22 and the range of d/b values is rather limited. In the field, much larger d/b values would be required in many cases.

In previous studies, velocity profiles were not measured and therefore no true mean velocities were established. From the centerline velocity profiles presented earlier, a depth averaged velocity (U) was calculated and compared to the "average" velocity V. Although U is not a true mean velocity either, it is expected to reflect the true mean velocity more closely than V. In computing U the values of $U/u_m \approx 0.525$ and $U/u'_m \approx 0.95$ were estimated from Fig. 20 (Denil 1) and Fig. 21 (Denil 2) respectively. The corresponding U values for Denil 3 were estimated from Fig. 16.

From Table 2, the ratios u_m/V, u'_m/V and U/V indicate, particularly for Denil 2 and 3, that the net flow area (bd or $b\bar{d}$) used for the computation of the "average" velocity V, even though it is convenient, it is rather small. In between the vanes, the flow depth and especially the flow width are considerably larger, resulting in much larger values for the flow area and thereby yielding much smaller values for the velocity V. Nevertheless, V proved a useful parameter in the estimation of the velocity scales (Fig. 22) and was utilized again in the prediction of the depth averaged velocity U. Fig. 23 presents the results of plotting U/V versus d/b. Although a slight slope effect is discernible for Denil 1, an average value of 0.75 for U/V is indicated. It is noteworthy that a slope effect is less apparent for Denil 2 where an average value of 0.50 for U/V is implied by Fig. 23, while for Denil 3 $U/V \approx 0.41$ could be used. For the slopes of 10.0%, 20.1% and 31.5% the corresponding average U/V ratios are (a) 0.87, 0.73, 0.63 for Denil 1, (b) 0.51, 0.40, 0.60 for Denil 2, and (c) 0.39, 0.43, 0.40 for Denil 3.

Besides u_m, u'_m, V and U, another useful parameter in characterizing the flow in the fishways is the Froude number (F). Here, the Froude number was based on the depth averaged velocity U and was computed from (Table 2):

$$F = \frac{U}{\sqrt{gd}} \text{ (Denil 1) or } F = \frac{U}{\sqrt{g\bar{d}}} \text{ (Denil 2,3)} \qquad (2)$$

where g is the acceleration due to gravity.

Froude number values of less than 1.0 indicate subcritical conditions in steady, uniform open channel flow. The average values for the Froude number (F), corresponding to the 10.0%, 20.1% and 31.5%

slopes tested, were estimated to be (a) 0.26, 0.31, 0.34 for Denil 1, (b) 0.24, 0.22, 0.38 for Denil 2, and (c) 0.20, 0.43, 0.53 for Denil 3.

HYDRAULIC ANALYSIS

At this stage, it would be instructive to compare the flow parameters of the Denil fishways to those of a plain rectangular channel. Consider then two channels set at the same bed slope (S_o) and carrying the same discharge (Q). One channel is the Denil 1 fishway and the other is a plain rectangular channel of width b, the same as the main stream in the fishway. Define q, V, d, R, n, and E as the discharge per unit width, the water velocity, the water depth, the hydraulic radius, the friction factor (Manning's), and the specific energy of flow for the fishway; the corresponding parameters for the plain channel are q_o, V_o, y_o, R_o, n_o, E_o. If F_o is the Froude number for the plain channel, the following relationships hold if steady, uniform flow is assumed in both channels:

$$q = \frac{Q}{b} = q_o \tag{3}$$

$$q = Vd = V_o y_o \tag{4}$$

$$E = d + \frac{V^2}{2g} \tag{5}$$

$$E_o = y_o + \frac{V_o^2}{2g} \tag{6}$$

$$V = \frac{M}{n} R^{2/3} S_o^{1/2} \tag{7}$$

$$V_o = \frac{M}{n_o} R_o^{2/3} S_o^{1/2} \tag{8}$$

$$F_o = \frac{V_o}{\sqrt{g y_o}} \tag{9}$$

where M is a constant dependent on the system of units used; M is 1.0 for m-s units and 1.486 for ft-s units.

From (4) and (9):

$$F_o^2 = \frac{V_o^2}{gy_o} = \frac{q^2}{gy_o^3}\text{, or } \frac{q^2}{g} = F_o^2 y_o^3 \qquad (10)$$

Also, from (9):

$$\frac{F_o^2}{2} = \frac{V_o^2}{2gy_o}\text{, or } \frac{V_o^2}{2g} = \frac{F_o^2 y_o}{2} \qquad (11)$$

Define the following dimensionless parameters:

$$\lambda = \frac{y_o}{d} \qquad (12)$$

$$\eta = \frac{y_o}{b} \qquad (13)$$

$$\xi = \frac{\eta_o}{\eta} \qquad (14)$$

$$\varepsilon = \frac{E - E_o}{E} = 1 - \frac{E_o}{E} \qquad (15)$$

From (12) and (13) readily follows that:

$$\frac{\eta}{\lambda} = \frac{d}{b} \qquad (16)$$

Equations (6) and (11) yield:

$$E_o = y_o + \frac{V_o^2}{2g} = y_o + \frac{F_o^2 y_o}{2} = y_o\,(1 + \frac{F_o^2}{2}),\text{ or}$$

$$E_o = y_o\,\frac{2 + F_o^2}{2} \qquad (17)$$

Combining (4), (5) and (10):

$$E = d + \frac{q^2}{2gd^2} = d + \frac{F_o^2 y_o^3}{2d^2} = d + \frac{F_o^2 y_o}{2}\,(\frac{y_o}{d})^2\text{, or}$$

$$E = y_o \left[\left(\frac{d}{y_o}\right) + \frac{F_o^2}{2} \left(\frac{y_o}{d}\right)^2 \right] \qquad (18)$$

Substituting (12) in (1[illegible]):

$$E = y_o \left(\frac{1}{\lambda} + \frac{F_o^2 \lambda^2}{2}\right), \text{ or } E = y_o \frac{2 + F_o^2 \lambda^3}{2\lambda} \qquad (19)$$

Dividing (17) by (19):

$$\frac{E_o}{E} = \frac{(2 + F_o^2)/2}{(2 + F_o^2 \lambda^3)/2\lambda} = \lambda \frac{2 + F_o^2}{2 + F_o^2 \lambda^3} \qquad (20)$$

Then (15) becomes:

$$\varepsilon = 1 - \lambda \frac{2 + F_o^2}{2 + F_o^2 \lambda^3} \qquad (21)$$

From (15) it is evident that ε is a measure of the energy dissipated in the fishway. It can also indicate fishway efficiency because the water velocity decreases as the energy dissipation increases. Decreasing water velocity to levels that are within the biokinetic range of fish is the main objective in the Denil fishways. Equation (21) shows that ε is a function of λ and F_o and provides an estimate of the energy dissipation in the fishway.

Further, from (4), (7) and (8):

$$q = V_o y_o = \frac{M}{n_o} y_o R_o^{2/3} S_o^{1/2}$$

$$q = Vd = \frac{M}{n} d R^{2/3} S_o^{1/2}$$

and therefore:

$$\frac{M}{n_o} y_o R_o^{2/3} S_o^{1/2} = \frac{M}{n} d R^{2/3} S_o^{1/2}, \text{ or}$$

$$y_o R_o^{2/3} = \frac{n_o}{n} d R^{2/3}, \text{ and recalling (14)}$$

$$\xi = \frac{n_o}{n} = \left(\frac{y_o}{d}\right)\left(\frac{R_o}{R}\right)^{2/3} \qquad (21)$$

By definition:

$$R_o = \frac{by_o}{b + 2y_o}; \; R = \frac{bd}{b + 2d} \qquad (22)$$

Then,

$$\frac{R_o}{R} = \frac{by_o(b + 2d)}{bd(b + 2y_o)} = \frac{y_o}{d}\left(\frac{1 + 2\frac{d}{b}}{1 + 2\frac{y_o}{b}}\right)$$

or, substituting (12), (13) and (16):

$$\frac{R_o}{R} = \lambda\,\frac{1 + 2\frac{\eta}{\lambda}}{1 + 2\eta} = \lambda\,\frac{\frac{\lambda + 2\eta}{\lambda}}{1 + 2\eta} = \lambda\,\frac{\lambda + 2\eta}{\lambda(1 + 2\eta)}, \text{ or}$$

$$\frac{R_o}{R} = \frac{\lambda + 2\eta}{1 + 2\eta} \qquad (23)$$

Utilizing (12) and (23), (21) may be rewritten as:

$$\xi = \frac{n_o}{n} = \lambda\left(\frac{\lambda + 2\eta}{1 + 2\eta}\right)^{2/3} \qquad (24)$$

From (21) and (24) it is evident that energy dissipation and flow resistance are linked through the parameter λ.

As evidenced by Fig. 22 and 23, the velocity V, which was defined by (1) or (4), may be used to estimate the maximum mean velocities and the depth averaged velocities expected in each fishway. The above analysis assists in the development of a simple method to predict V. Equation (8) could be rewritten as:

$$\frac{n_o Q}{M\sqrt{S_o}\,b^{8/3}} = f(\eta) \qquad (25)$$

where $\eta = \frac{y_o}{b}$.

Equation (25) has been tabulated by Posey (1942) for given values of Q, n_o, S_o and b, so η and hence y_o can easily be calculated. For each of the present series of experiments y_o and V_o have been calculated and given in Table 2.

Further, for Denil 1, if τ_o is the average shear stress exerted by the surrounding fluid on the three wetted boundaries of the mainstream of the fishway, for a unit length of the fully-developed part of the flow:

$$bd\gamma S_o - c_f \frac{\rho V^2}{2} (b + 2d) = 0 \tag{26}$$

$$\tau_o = c_f \frac{\rho V^2}{2} \tag{27}$$

wherein b is the width and d is the depth of the main stream in the fishway, γ is the specific weight and ρ is the mass density of the water, and c_f is the coefficient of fluid friction. Combining (26) with (4) and after simplification,

$$c_f = \frac{n_o^{\,2}}{M^2} \frac{2g}{y_o^{\,1/3}} \frac{(1 + 2\eta)^{4/3}}{(1 + 2\eta \frac{V_o}{V})} \left(\frac{V_o}{V}\right)^3 \tag{28}$$

For the Denil 2 and Denil 3 fishways, the only difference will be to replace d by $\bar{d}$ in equations (4) to (28).

Using experimental observations on V and (25) to calculate y_o and V_o, c_f was calculated for each experiment and the calculated values are shown in Table 2. It is interesting to find out that the c_f values are of the order of 1 for the Denil 1 fishway whereas for rigid boundary friction, c_f is many times smaller (typically of the order of 10^{-3}).

For the Denil 1 fishway, Fig. 24a shows that c_f decreases with increasing d/b. Perhaps for approximate calculations, c_f could be given an average value of 0.8 for d/b in the range of 0.5 to 1.4. With such an average value, for Denil 1, using (26) and the continuity (or mass conservation) equation:

$$Q = bdV \tag{29}$$

for any given S_o, b and Q, V and hence d can easily be obtained. If the variation of c_f is to be retained, then a trial and error procedure will be needed.

For the Denil 2 fishway, if the two data points of the 2C series that are located away from others are discounted in Fig. 24b, then an average value of about 0.4 is indicated in the range of d/b studied. From Fig. 24c, for the Denil 3 fishway, an average value of 0.25 is indicated.

If c_f is taken as an index for the efficiency of the fishways, Denil 1 is the most efficient and Denil 3 the least efficient. It is interesting to note that all three fishways maintained subcritical flow with Froude numbers less than 0.67 (Table 2) even for the steepest slope of 31.5%. Further, Table 2 provides values of V/V_o. For Denil 1, 2 and 3, V/V_o values of approximately 0.18, 0.22 and 0.30 are indicated, respectively. Using the continuity equation, the corresponding values for the depth ratios would be 5.6, 4.6 and 3.3 for Denil 1, 2 and 3 respectively.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

1. The velocity profiles in the central plane of Denil 1, have been found to have a characteristic shape with the maximum velocity filament to be located at the bottom of the main stream. These velocity profiles for the three slopes and three discharges have been described by one "similarity curve". The scales for this "similarity curve" have been correlated with the main parameters of the flow.

2. An analysis has been developed for predicting the mean velocity and the depth of the main stream for all the three fishways. This analysis introduces a coefficient of friction (c_f) between the main stream and the recirculating flow on the sides and the bottom. For the Denil 1, this coefficient is of the order of unity which is about 100 times larger than the skin friction coefficient known for traditional open channel flow.

3. The similarity of the central plane velocity profiles was found to hold for Denil 2 also. The main difference appears to be that for Denil 2 the maximum velocity filament is located near the surface of the main stream. The scales for the "similarity curve" for this fishway have also been correlated.

4. The coefficient of friction for the second fishway has been found to be somewhat less than that of the first fishway.

5. For the third fishway the data on the velocity profiles are rather inconclusive regarding the similarity aspect. Further, the friction coefficient for Denil 3 is only about 1/3 of the corresponding

values for Denil 1.

6. The flow was subcritical for all three fishways and for all conditions tested. The Froude number ranged from 0.24 to 0.35 for Denil 1, from 0.18 to 0.46 for Denil 2, and from 0.19 to 0.67 for Denil 3.

7. The depth averaged centerline velocity for the main stream in Denil 1 was only about 14% of the velocity that would exist in a flume (without vanes) for the same slope and discharge. The corresponding percentages for Denil 2 and 3 were about 11% and 12% respectively. It would appear then that all three fishways are very efficient in reducing water velocities.

RECOMMENDATIONS

1. To extend the results of the present study to cover a larger range of depths, it would be necessary to do further studies with much larger values of d/b. Scale models would be required since such studies could not be conducted in the laboratory using prototype dimensions. Definitive experiments to establish the validity of scale models for these types of fishways would be worthwhile.

2. Different values of b would be needed to accommodate very small or very large fish species. Further experiments need to be made with varying values for b.

3. The spacing and the angles of inclination of the vanes, the width of the recirculation region formed by the vanes and the arrangement of the bottom fins should be studied, preferably in the laboratory.

4. Some experiments on smaller slopes may be desirable, particularly if juvenile fish need to be accommodated.

5. Field studies of these designs are very important and should be carried out. Continuous interaction between field and laboratory studies should be ensured.

The effectiveness of this short study in understanding the working of these fishways was surprising; nevertheless only a small part of the total field of the hydraulics of fishways was investigated. For further studies in this area to be effective and useful (for people as well as fish!) very close collaboration should exist between fisheries biologists and scientists, water resources engineers, planners and scientists.

Table 1. Characteristic dimensions for Denil Fishways.

Reference	Design Type	b (mm)	B (mm)	Y (mm)	a (mm)	k (mm)	Max. d/b	B/b	a/b	k/b
McLeod and Nemenyi (1941)	Model 1 (Fig. 6)	114	203	197	95	44	1.34	1.78	0.83	0.39
	Model 2, 4	140	203	254	95	51	1.45	1.45	0.68	0.36
	Model 3	254	406	610	203	102	2.00	1.60	0.80	0.40
	Model 5, 6	76	152	254	51	0	3.33	2.00	0.67	0.00
White and Nemenyi (1942)	Model 8 (Fig. 6)	101.5	203^E	-	76^E	29^E	-	2.00	0.75	0.29
Ziemer (1962)	Steeppass (Fig. 7)	356	559	686	254	127	1.57	1.57	0.71	0.36
Committee on Fish-Passes (1942)	Denil (Fig. 8)	533	914	1067	610	152	1.71	1.71	1.14	0.29
Fulton et al (1953)	Denil (Fig. 8)	762	1302	2134	864	207	2.80	1.71	1.13	0.27
Decker (1967)	Denil (Fig. 8)	711 to 356	1219 to 610	1293 to 862	813 to 457	216 to 108	1.82 to 2.42	1.71	1.14	0.30
Larinier (1981)	Denil (Fig. 8)	175	300	300	-	49	1.43	1.71	-	0.28
Present Study	Denil 1 (Fig. 7)	355	560	690	254	130	1.18	1.58	0.72	0.37
	Denil 2 (Fig. 8)	355	560	690	254	130	1.18	1.58	0.72	0.37
	Denil 3 (Fig. 8)	355	560	690	381	130	1.10	1.58	1.07	0.37

E - Estimated

Table 2. Experimental Observations

Experiment	S_o	Q(L/s)	d(cm)	$\bar{d}$(cm)	V(cm/s)	u_m(cm/s)	u'_m(cm/s)	u_m/V	u'_m/V	d/b	y_o(cm)	V_o(cm/s)	c_f	V/V_o	U/V	F
1A2	0.100	56.6	31.4		50.8	79.5		1.56		0.885	5.41	294.4	0.880	0.17	0.82	0.24
1A3	0.100	85.0	41.7		57.4	100.5		1.75		1.175	7.11	336.0	0.752	0.17	0.92	0.26
1A4	0.100	113.3	48.4		65.9	110.3		1.67		1.363	8.64	368.7	0.592	0.18	0.88	0.27
1B2	0.201	56.6	23.8		67.0	78.1		1.17		0.670	4.27	373.0	0.933	0.18	0.61	0.27
1B3	0.201	85.0	32.6		73.4	105.0		1.43		0.918	5.62	425.1	0.855	0.17	0.75	0.31
1B4	0.201	113.3	39.7		80.4	127.5		1.59		1.118	7.04	452.5	0.692	0.18	0.83	0.34
1C2	0.315	56.6	20.7		77.0	93.0		1.21		0.583	3.70	430.4	1.032	0.18	0.63	0.34
1C3	0.315	85.0	26.6		90.0	105.0		1.17		0.749	4.80	497.6	0.850	0.18	0.61	0.34
1C4	0.315	113.3	33.5		95.3	120.0		1.26		0.944	5.80	549.0	0.829	0.17	0.66	0.35
2A2	0.100	56.6	29.8	23.3	68.4		30.0		0.44	0.839	5.47	292.5	0.421	0.23	0.42	0.19
2A3	0.100	85.0	37.4	30.9	77.5		33.0		0.43	1.054	7.21	332.6	0.362	0.23	0.40	0.18
2A4	0.100	113.3	42.0	35.5	89.9		62.0		0.69	1.183	8.88	359.6	0.272	0.25	0.66	0.32
2B2	0.201	56.6	26.8	20.3	78.5		36.0		0.46	0.755	4.33	368.5	0.608	0.21	0.44	0.24
2B3	0.201	85.0	32.9	26.4	90.7		33.0		0.36	0.927	5.75	415.3	0.483	0.22	0.35	0.19
2B4	0.201	113.3	39.0	32.5	98.2		43.0		0.44	1.099	6.92	461.0	0.458	0.21	0.42	0.23
2C2	0.315	56.6	23.0	16.5	96.6		61.5		0.64	0.648	3.66	436.1	0.611	0.22	0.60	0.46
2C3	0.315	85.0	32.6	26.1	91.7		67.5		0.74	0.918	4.88	490.6	0.777	0.19	0.70	0.40
2C4	0.315	113.3	39.6	33.1	96.4		51.0		0.53	1.115	5.93	530.7	0.753	0.18	0.50	0.27
3A2	0.100	56.6	28.3	21.8	73.1	56.3		0.77		0.797	5.47	292.5	0.358	0.25	0.41	0.21
3A3	0.100	85.0	35.9	29.4	81.4	57.0		0.70		1.011	7.21	332.6	0.322	0.24	0.42	0.20
3A4	0.100	113.3	39.0	32.5	98.2	76.5		0.78		1.099	8.88	359.6	0.221	0.27	0.35	0.19
3B2	0.201	56.6	17.6	11.1	143.6	78.0		0.54		0.496	4.33	368.5	0.131	0.39	0.45	0.61
3B3	0.201	85.0	25.2	18.7	128.0	56.3		0.44		0.710	5.75	415.3	0.208	0.31	0.45	0.42
3B4	0.201	113.3	35.9	29.4	108.6	73.5		0.67		1.011	6.92	461.0	0.361	0.24	0.41	0.26
3C2	0.315	56.6	17.6	11.1	143.6	84.0		0.58		0.496	3.66	436.1	0.221	0.33	0.49	0.67
3C3	0.315	85.0	20.7	14.2	168.6	62.0		0.37		0.583	4.88	490.6	0.172	0.34	0.36	0.51
3C4	0.315	113.3	26.8	20.3	157.2	57.0		0.36		0.755	5.93	536.7	0.232	0.29	0.36	0.40

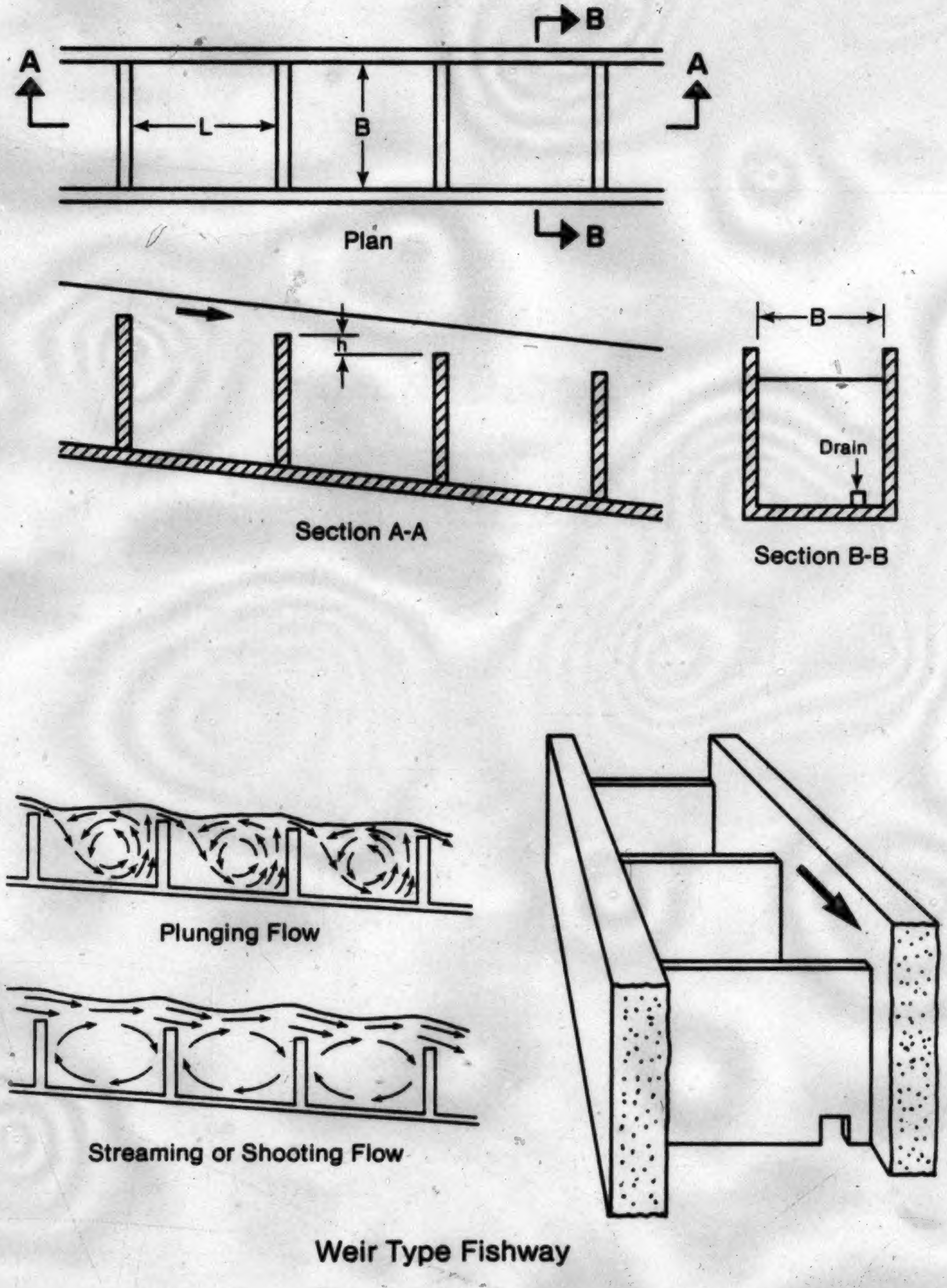
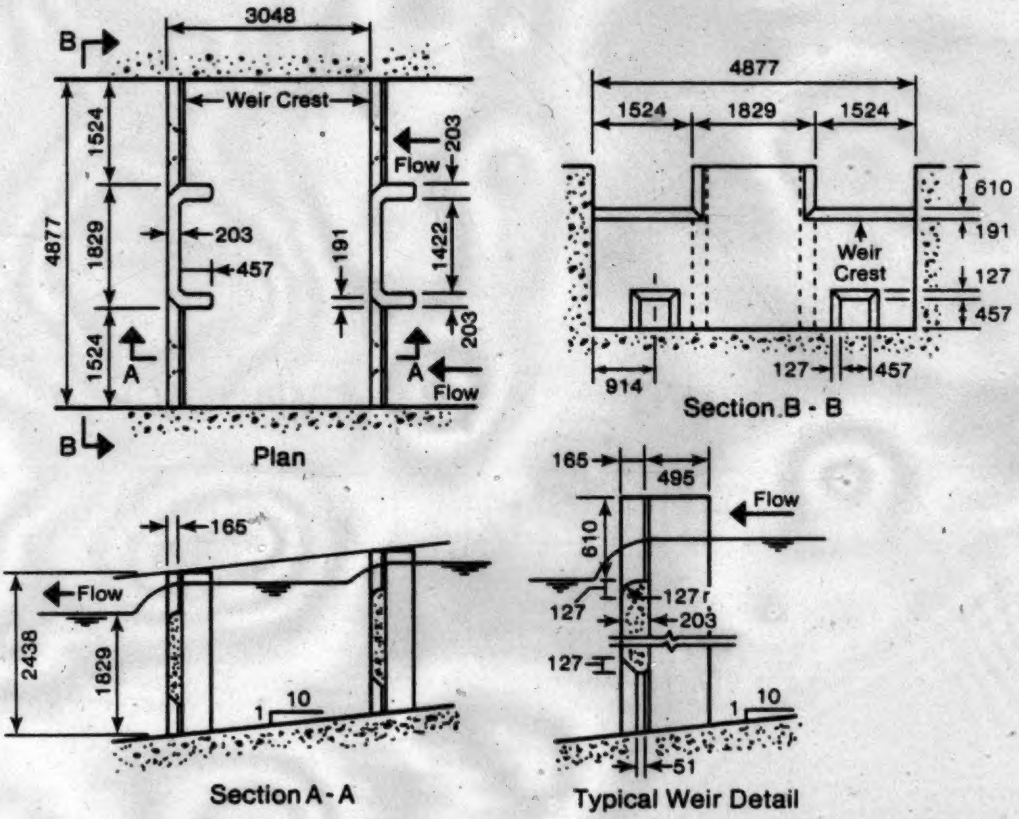
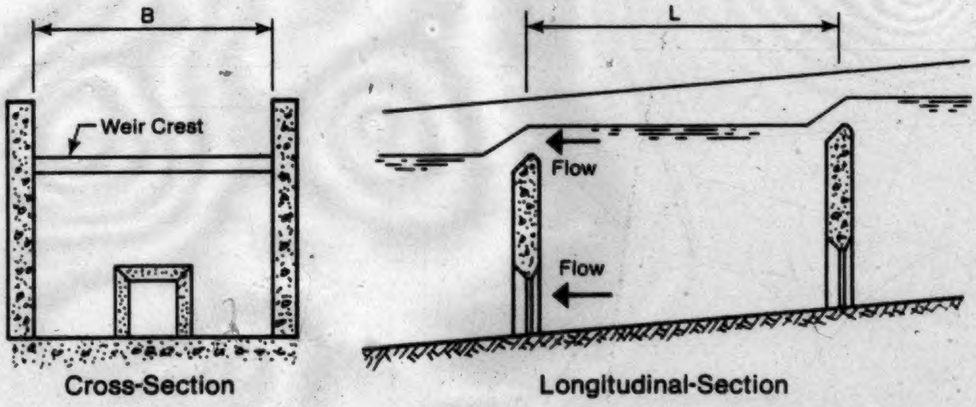


FIG. 1. A schematic of the weir type fishway.



Ice Harbor Dam Fishway (north fish ladder), State of Washington



Pool and Weir Fishways, Orifice-Weir Types

FIG. 2. Ice Harbor Dam fishway (Perkins 1974; all dimensions in mm) and a schematic of the orifice-weir type.

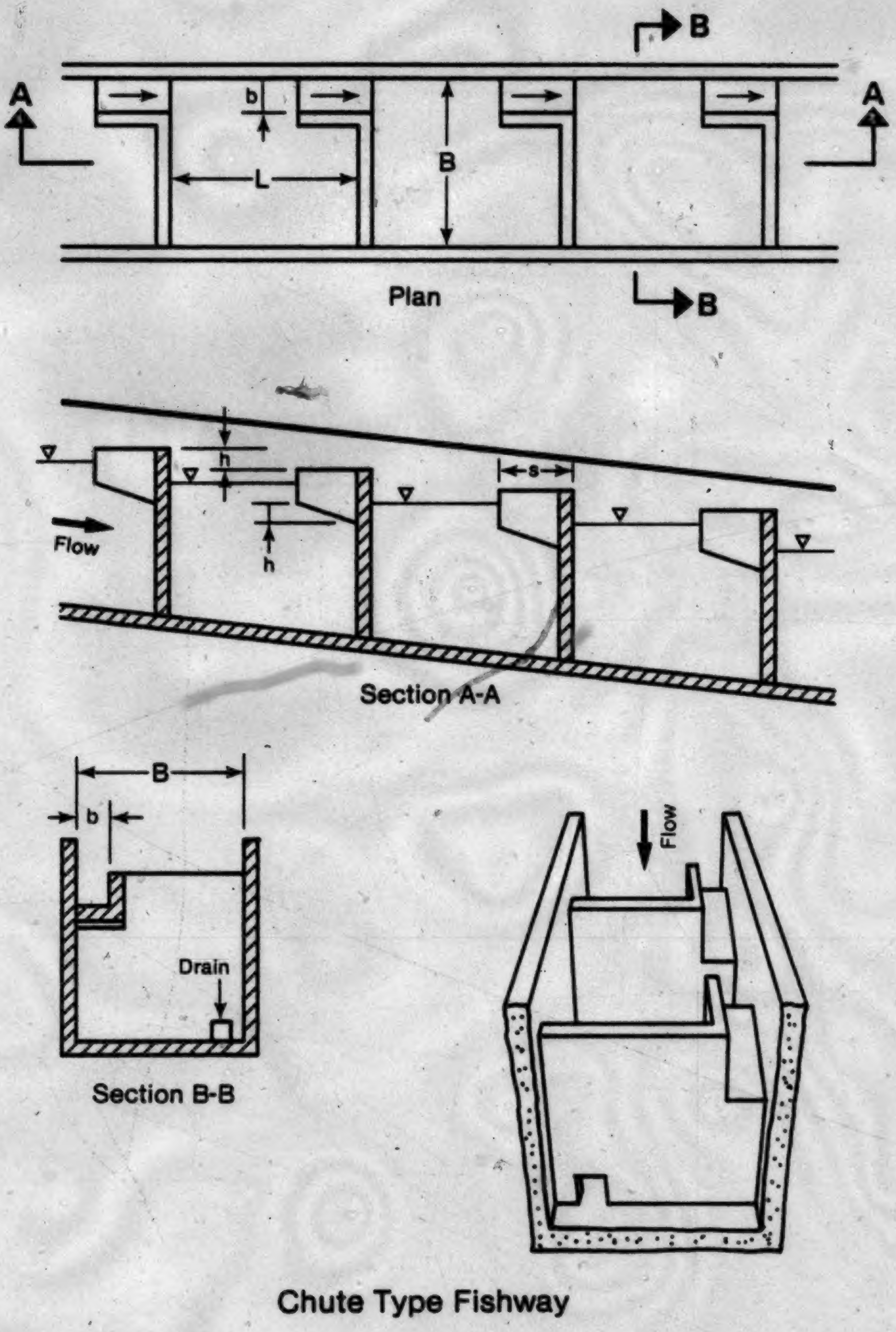


FIG. 3. A schematic of the chute type fishway.

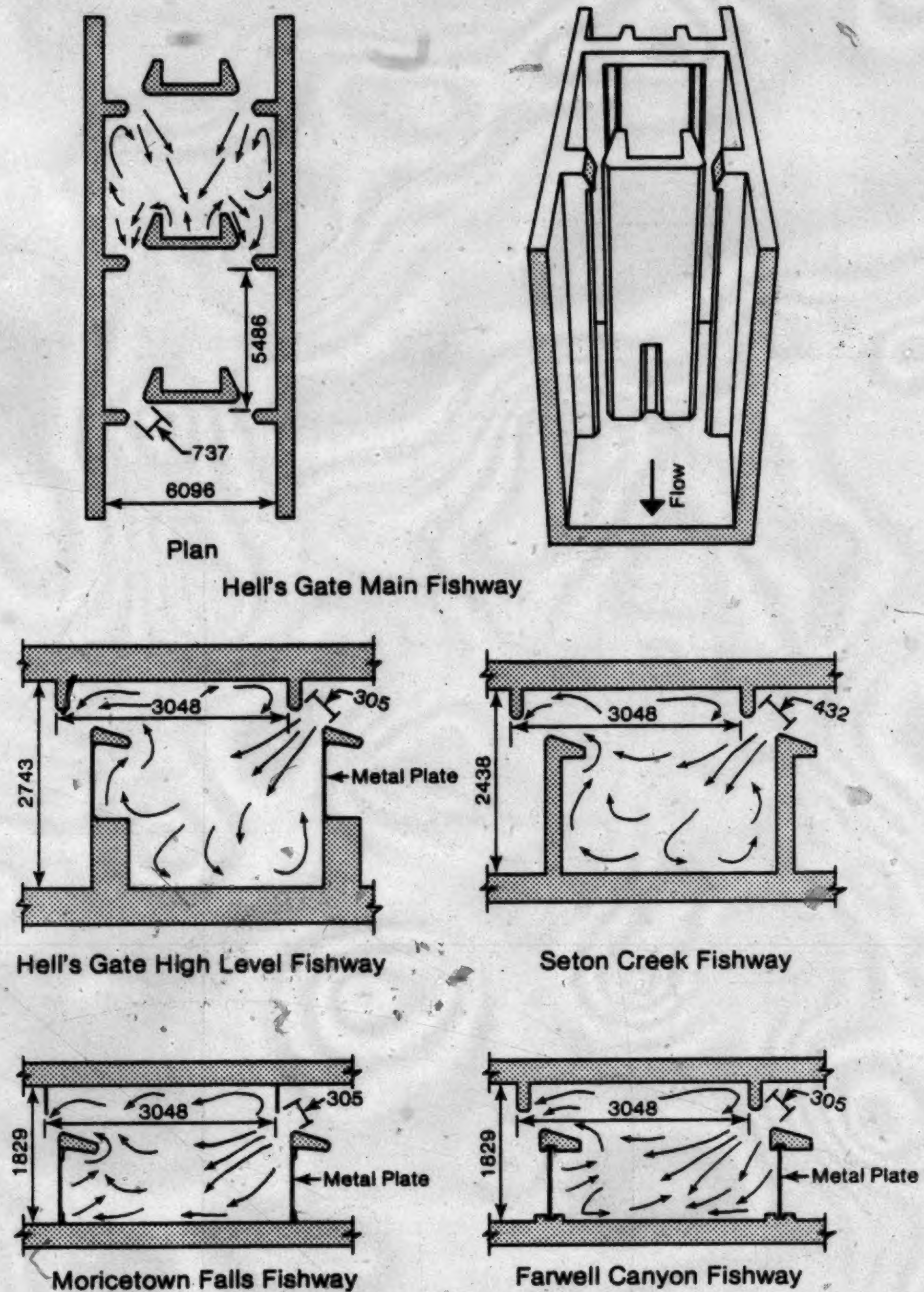


FIG. 4. Examples of vertical slot fishways in British Columbia (Clay 1961; all dimensions in mm).

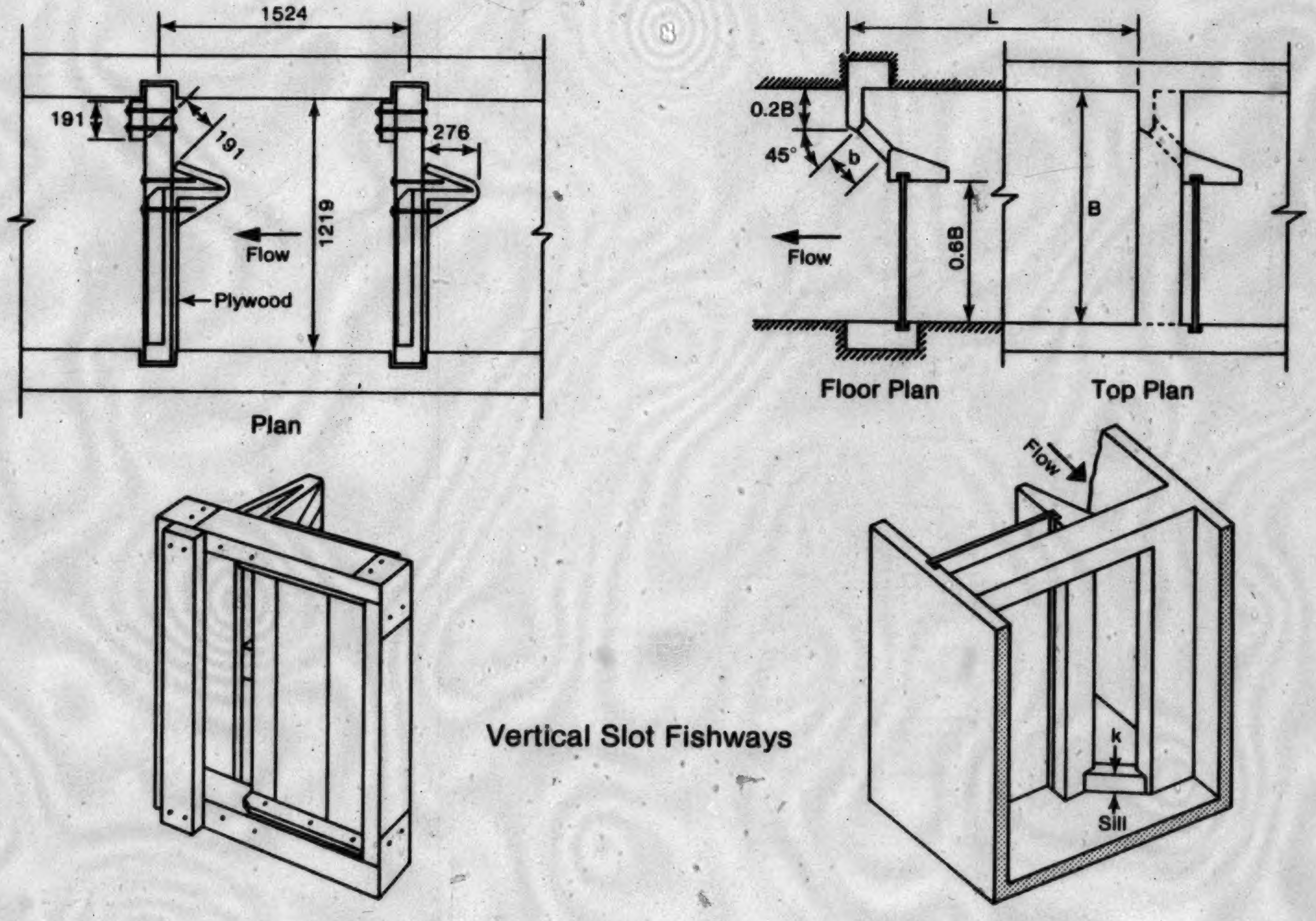


FIG. 5. A vertical slot fishway for trout (Clay 1961; timber construction, all dimensions in mm) and a generalized schematic of the vertical slot fishway.

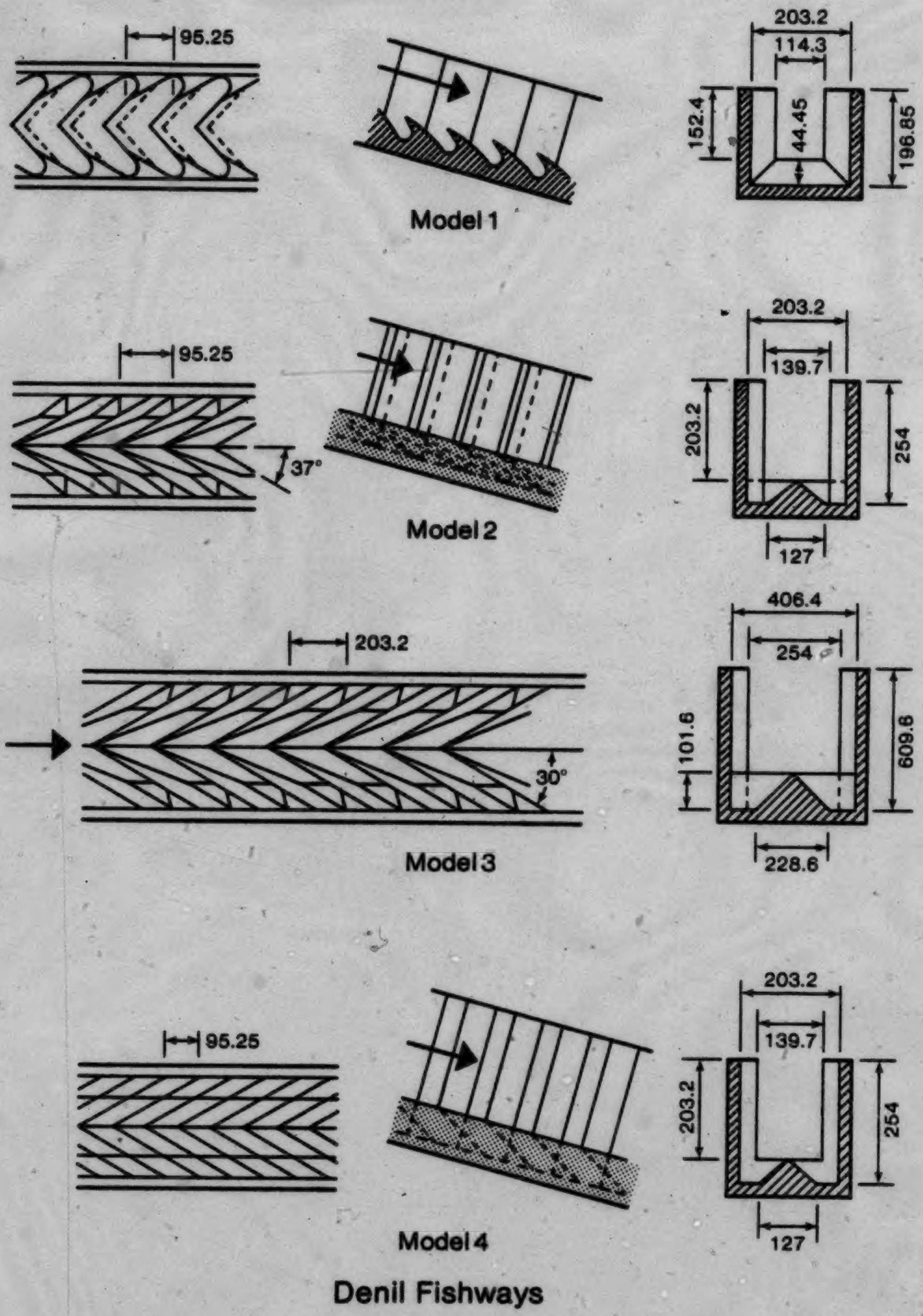
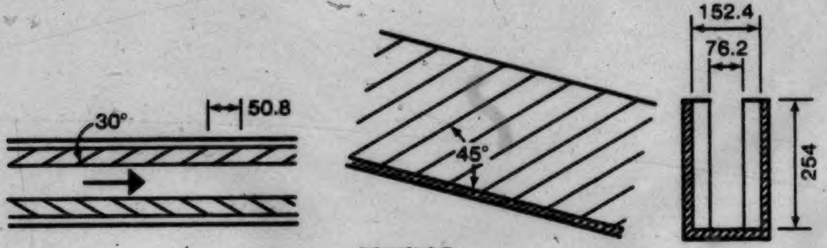
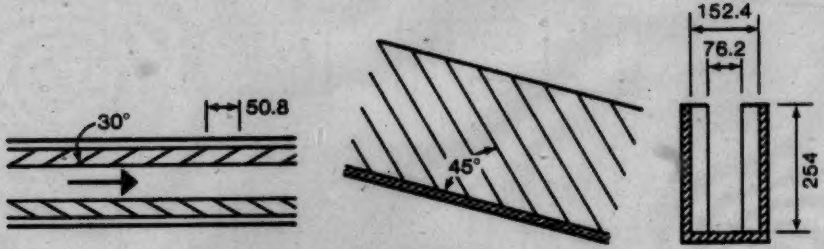


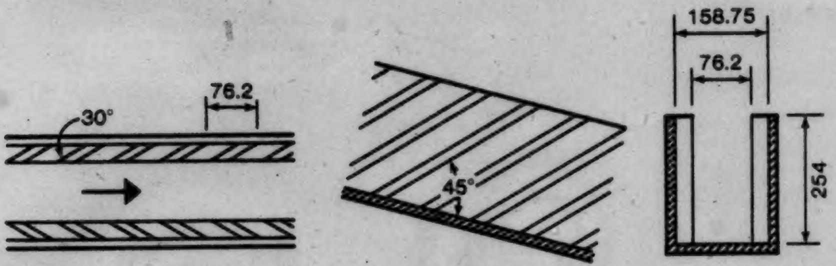
FIG. 6. Model Denil fishways (all dimensions in mm).



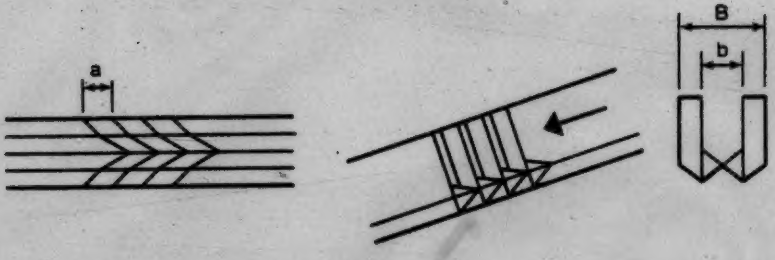
Model 5



Model 6

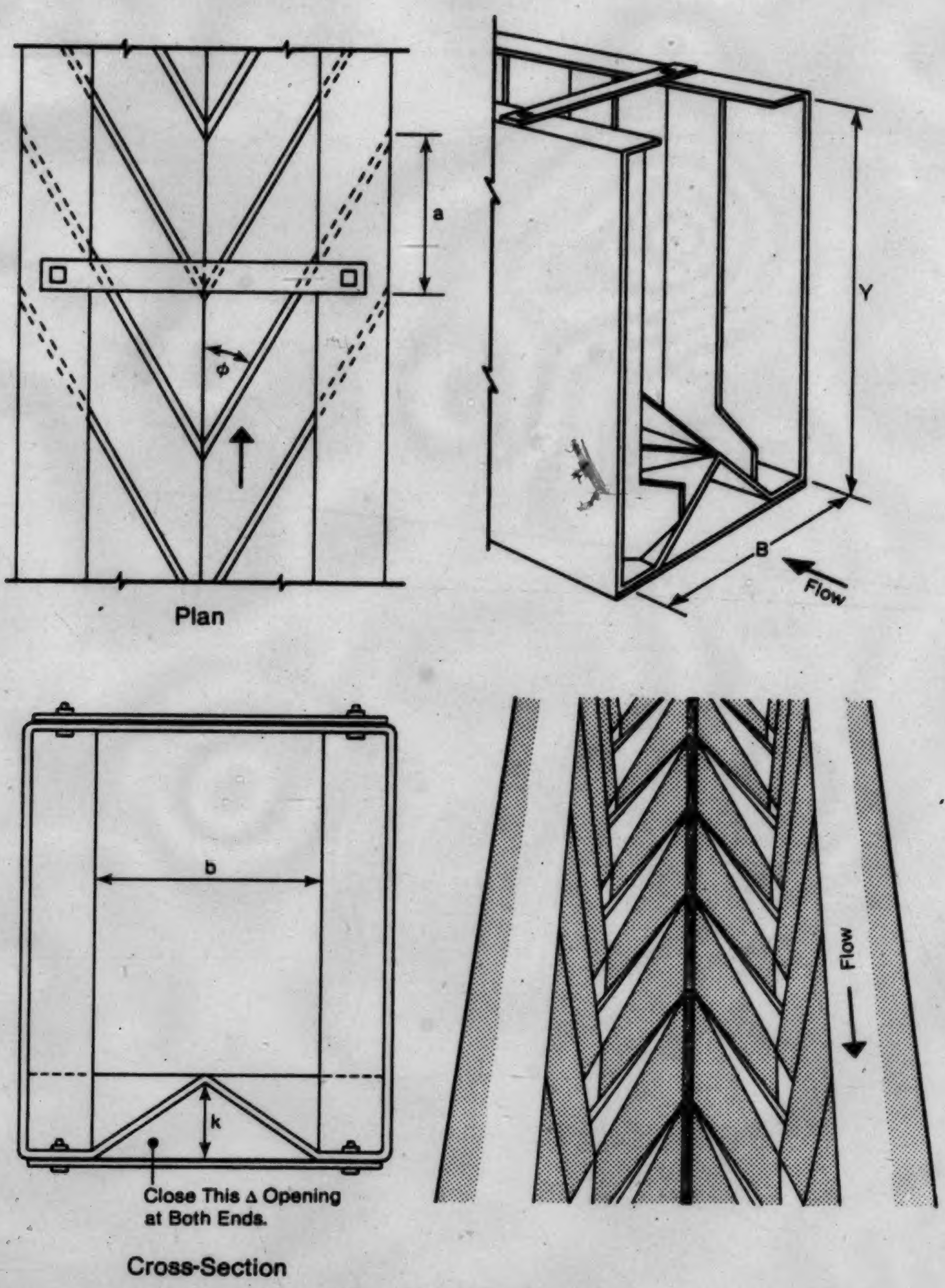


Model 7



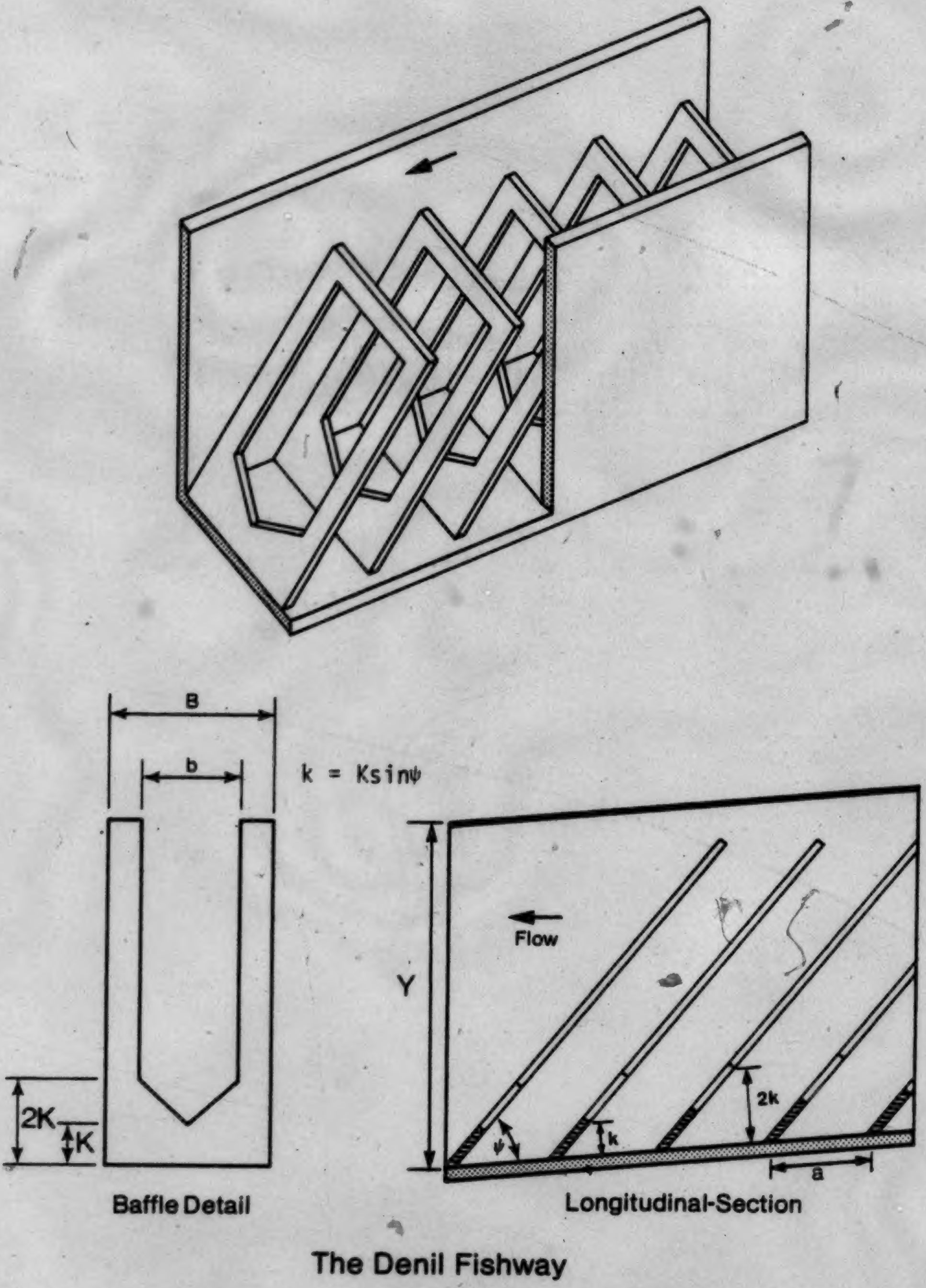
Model 8

Denil Fishways



The Steeppass

FIG. 7. A schematic of the steeppass (Denil 1).



Baffle Detail

Longitudinal-Section

The Denil Fishway

FIG. 8. A schematic of the Denil fishway (Denil 2 and 3).

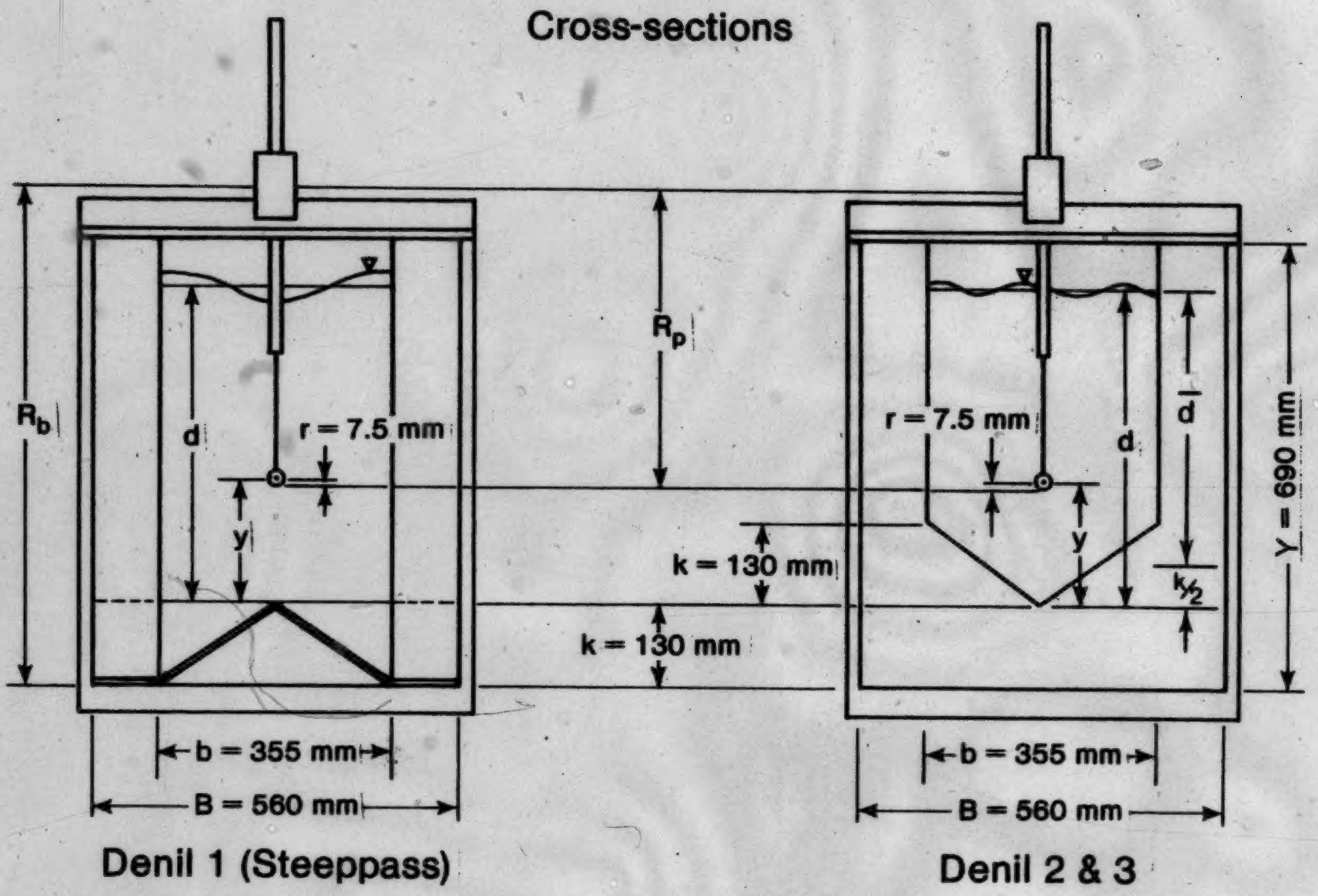
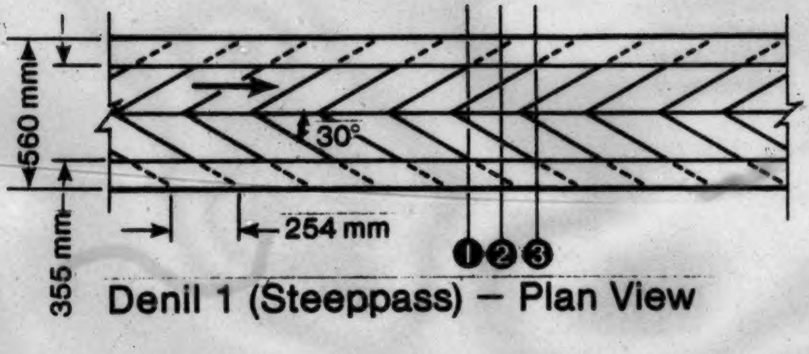
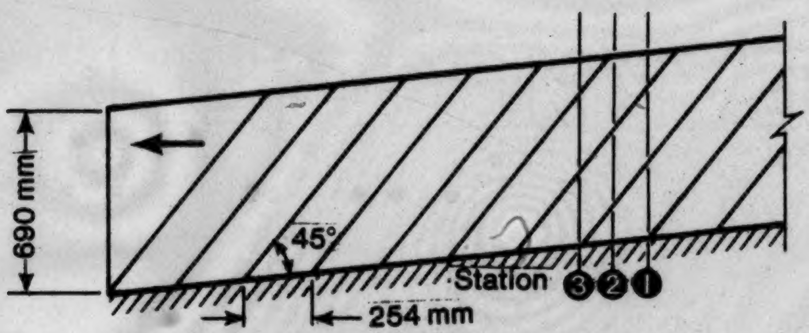


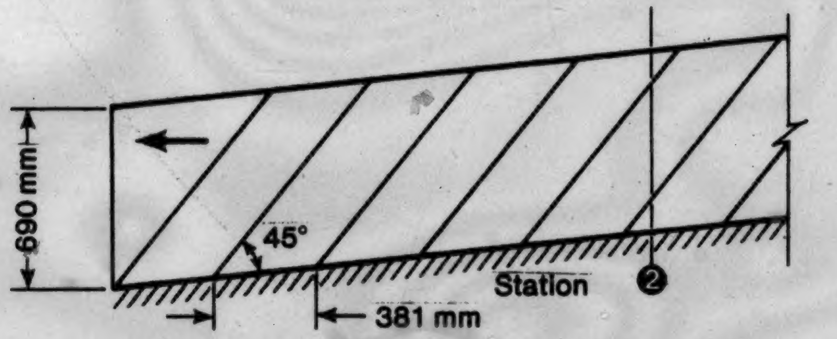
FIG. 9. Cross-sectional details



Denil 1 (Steeppass) – Plan View



Denil 2 – Longitudinal Section



Denil 3 – Longitudinal Section

FIG. 10. Vane spacing and hydrometric stations.

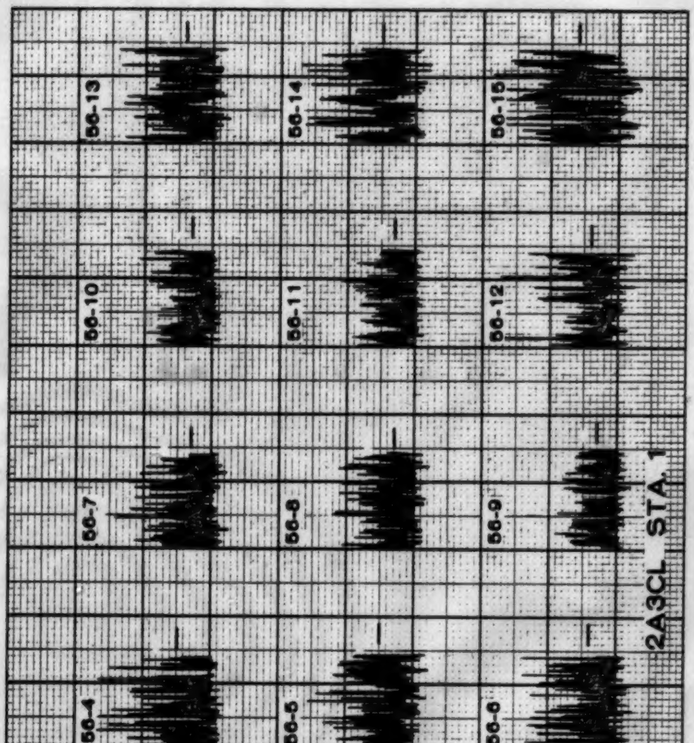


FIG. 11. Sample output from velocity recorder.

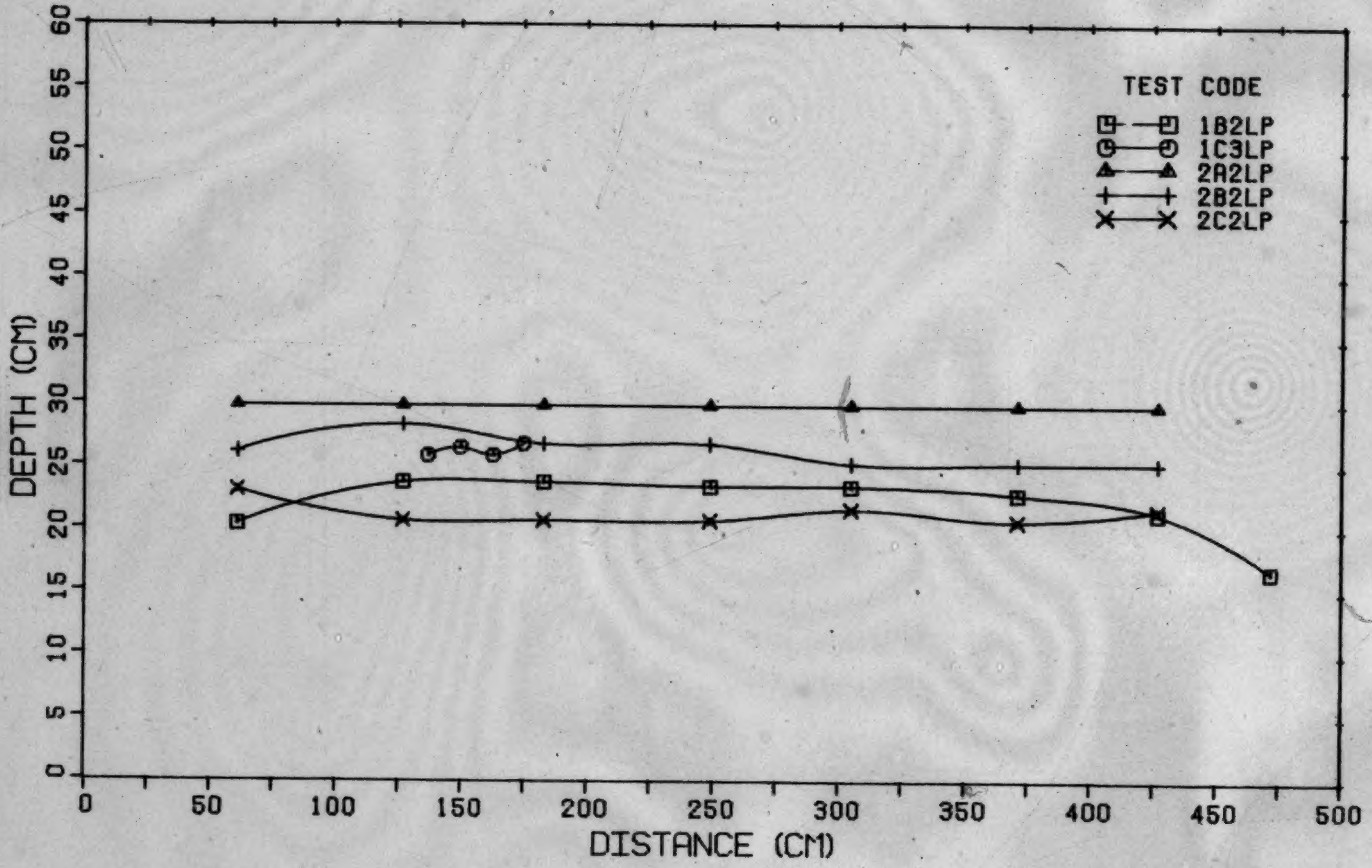


FIG. 12. Water surface profiles, along the centerline of the fishways.

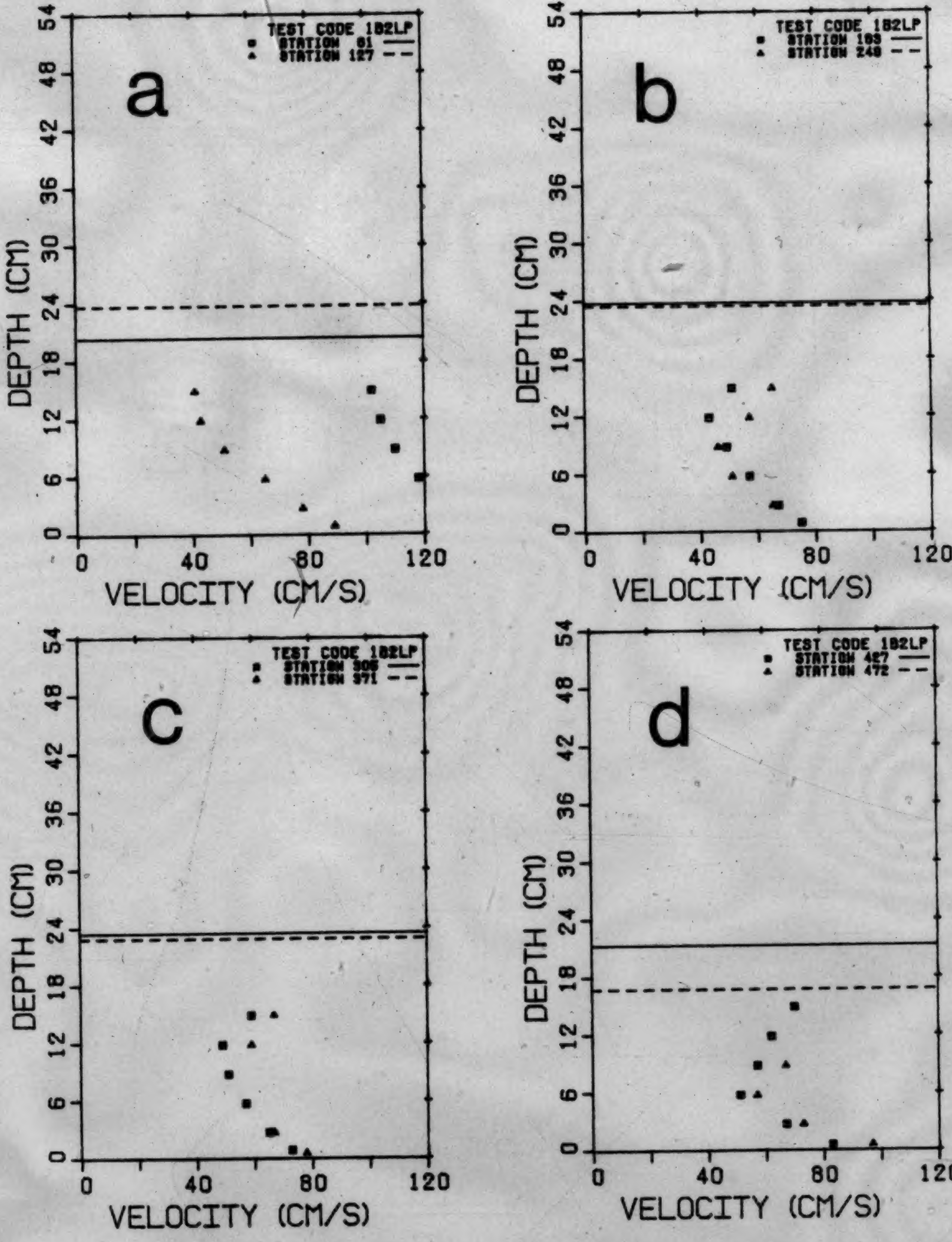
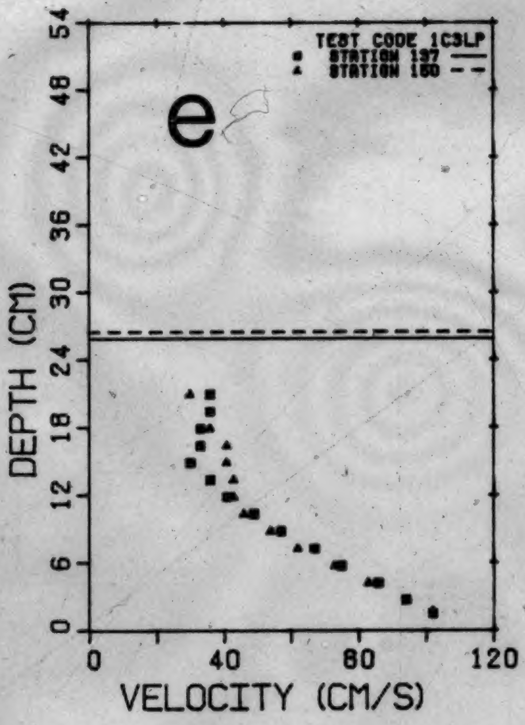
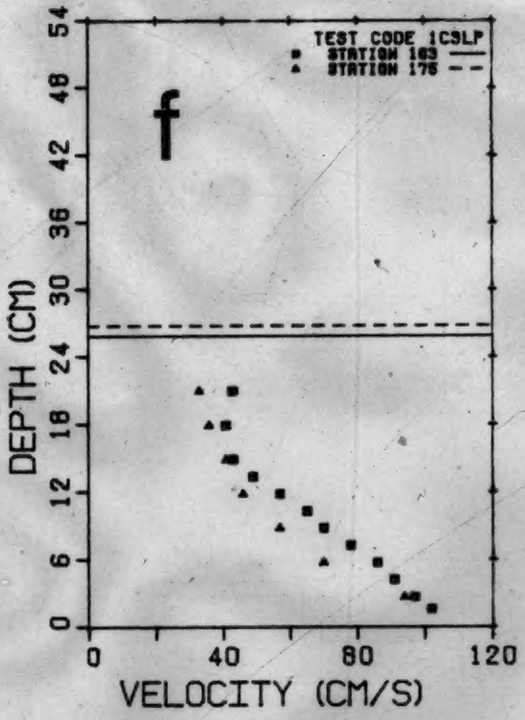
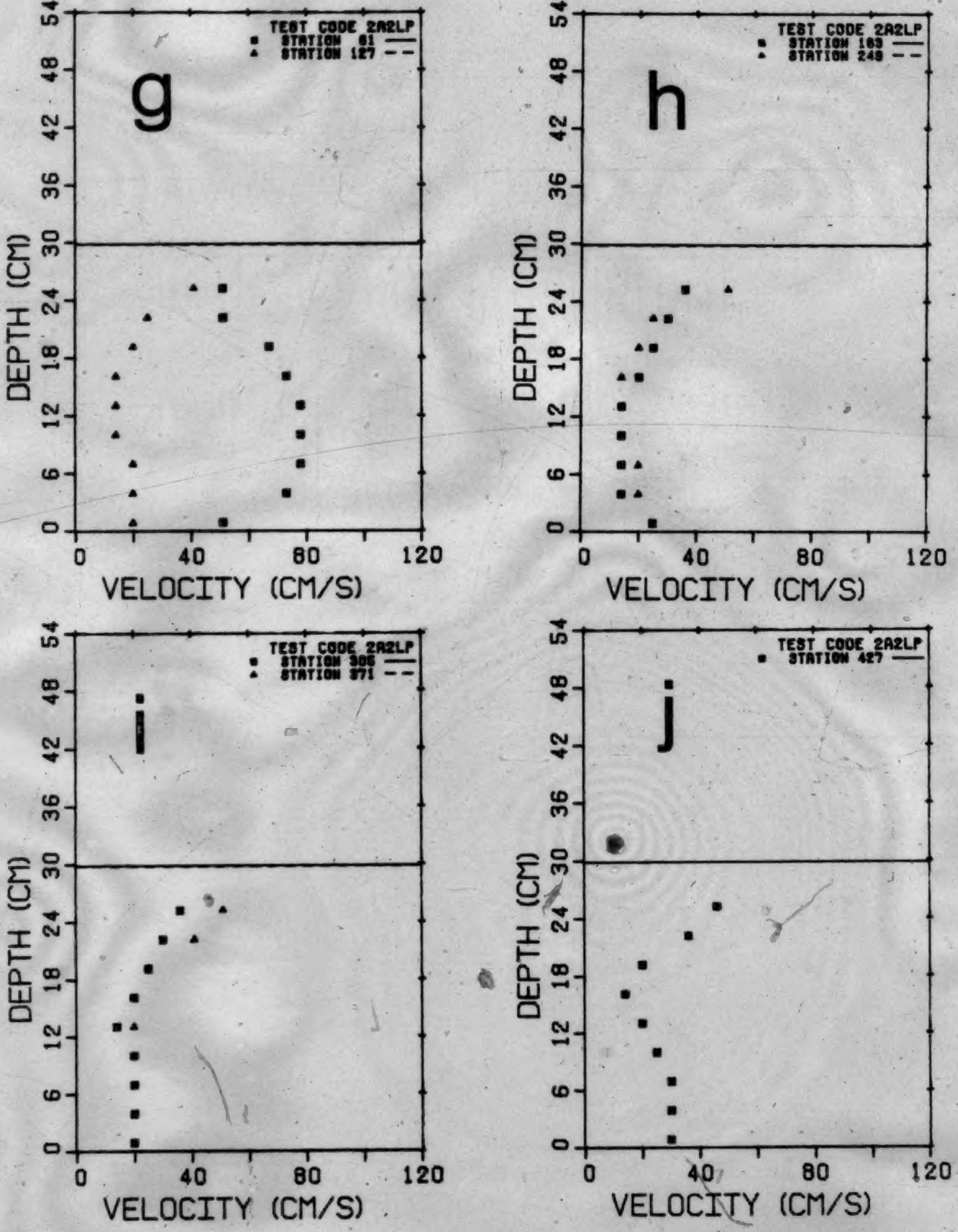
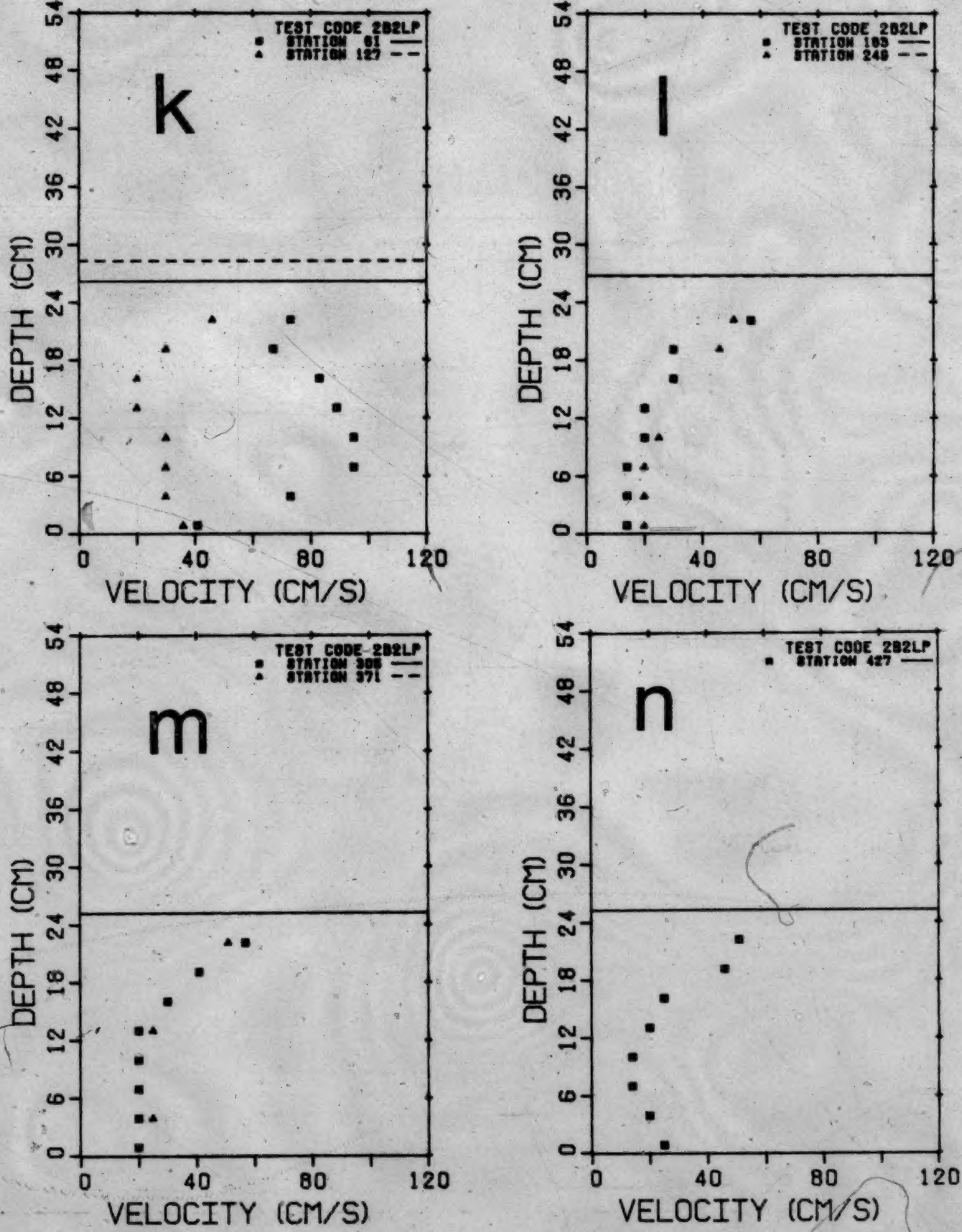


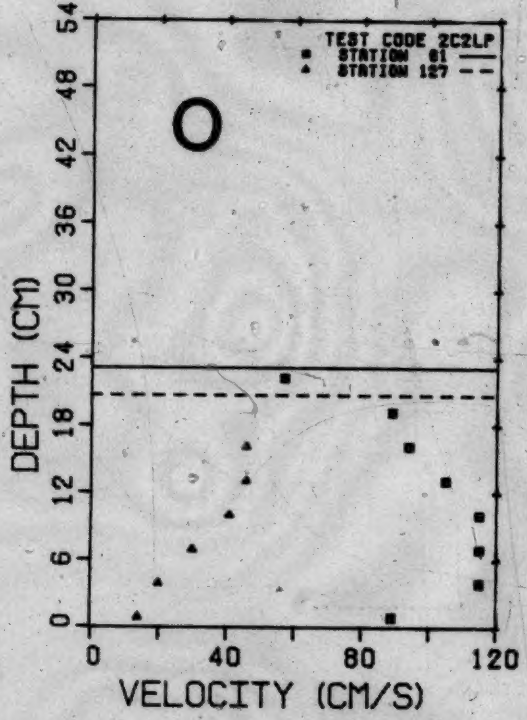
FIG. 13. Velocity profiles along the centerline of the fishways.

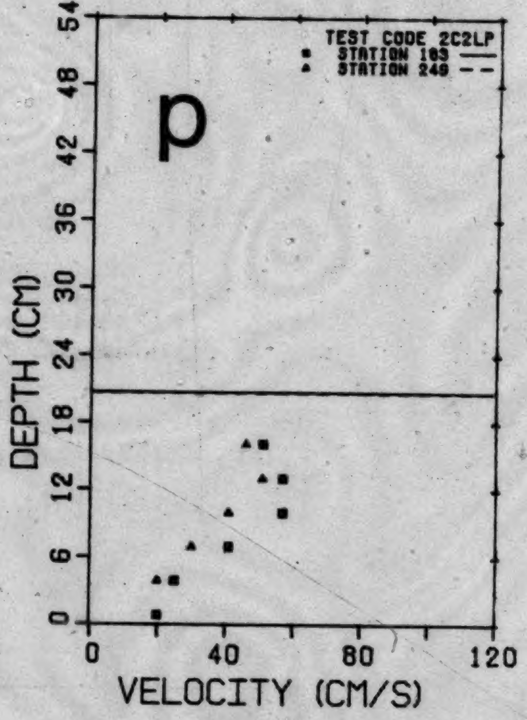

TEST CODE 1C3LP
■ STATION 137 ——
▲ STATION 150 - -
e
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

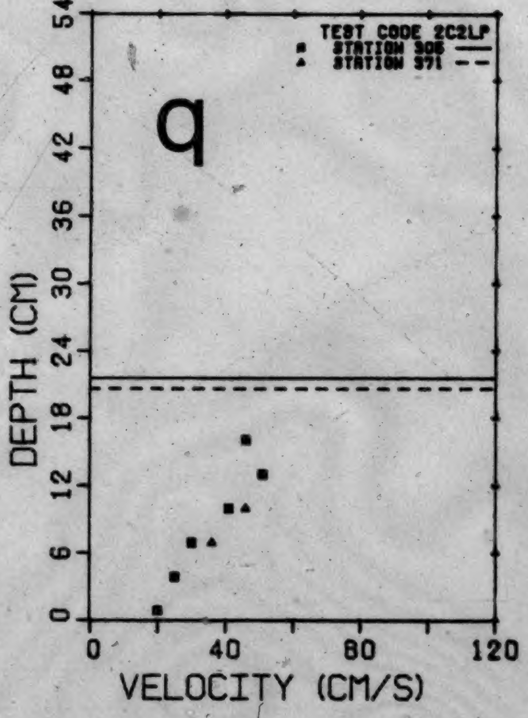

TEST CODE 1C3LP
■ STATION 163 ——
▲ STATION 176 - -
f
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

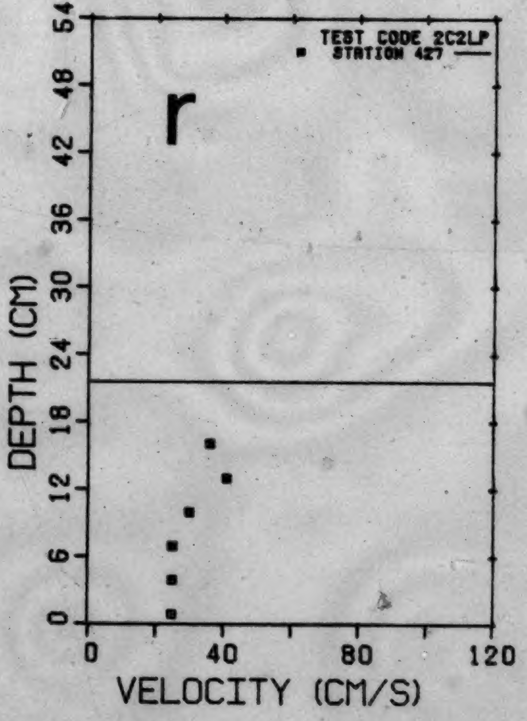

g
TEST CODE 2A2LP
■ STATION 81 ——
▲ STATION 127 - -
DEPTH (CM)
VELOCITY (CM/S)
0
6
12
18
24
30
36
42
48
54
0
40
80
120
h
TEST CODE 2A2LP
■ STATION 183 ——
▲ STATION 249 - -
DEPTH (CM)
VELOCITY (CM/S)
i
TEST CODE 2A2LP
■ STATION 306 ——
▲ STATION 371 - -
DEPTH (CM)
VELOCITY (CM/S)
j
TEST CODE 2A2LP
■ STATION 427 ——
DEPTH (CM)
VELOCITY (CM/S)


k
TEST CODE 2B2LP
■ STATION 61 ——
▲ STATION 127 – –
l
TEST CODE 2B2LP
■ STATION 183 ——
▲ STATION 249 – –
m
TEST CODE 2B2LP
■ STATION 305 ——
▲ STATION 371 – –
n
TEST CODE 2B2LP
■ STATION 427 ——
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120


o
TEST CODE 2C2LP
■ STATION 61 ——
▲ STATION 127 – –
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120


p
TEST CODE 2C2LP
■ STATION 183 ——
▲ STATION 249 – –
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120


q
TEST CODE 2C2LP
■ STATION 306 ——
▲ STATION 371 – –
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120


r
TEST CODE 2C2LP
■ STATION 427 ——
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

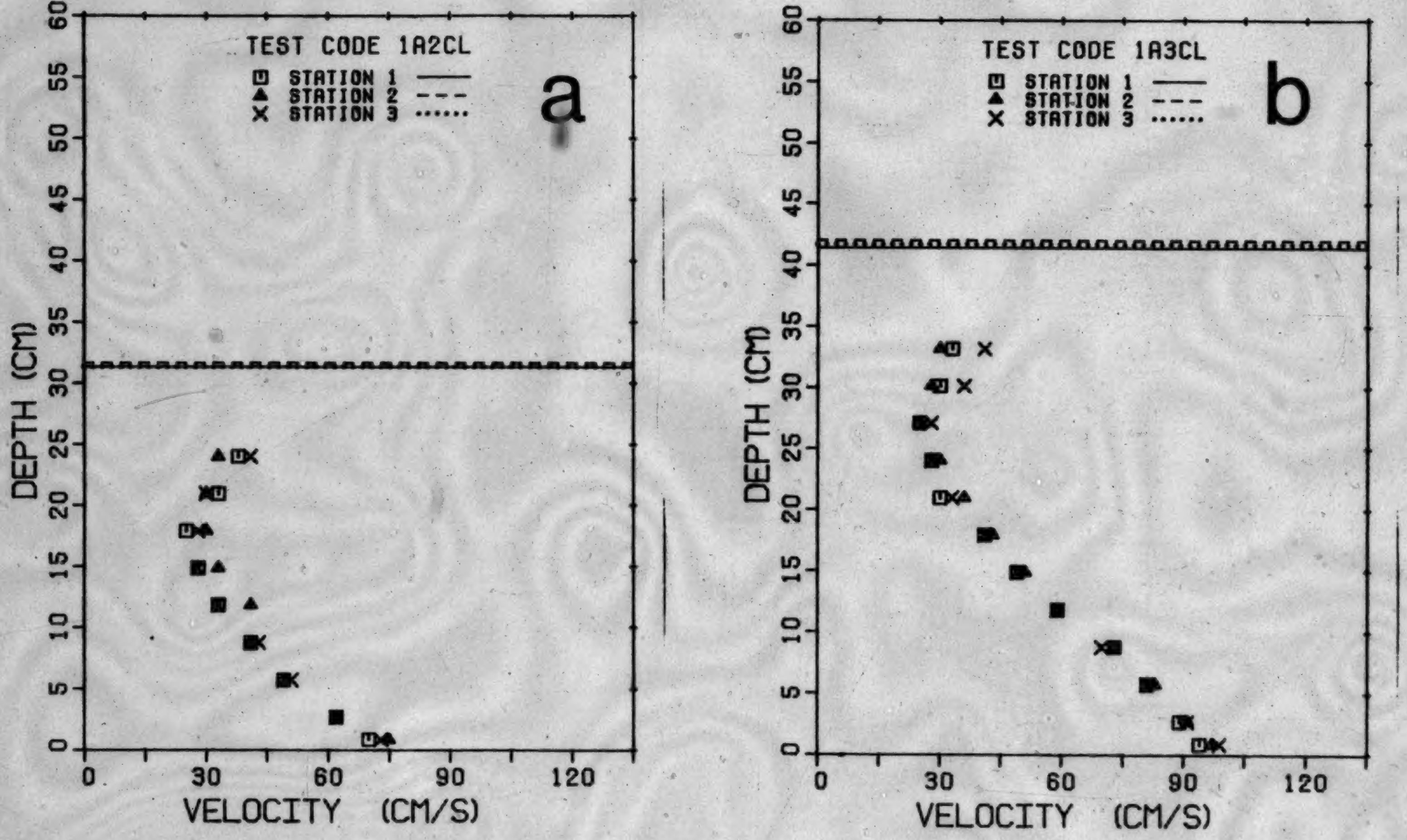
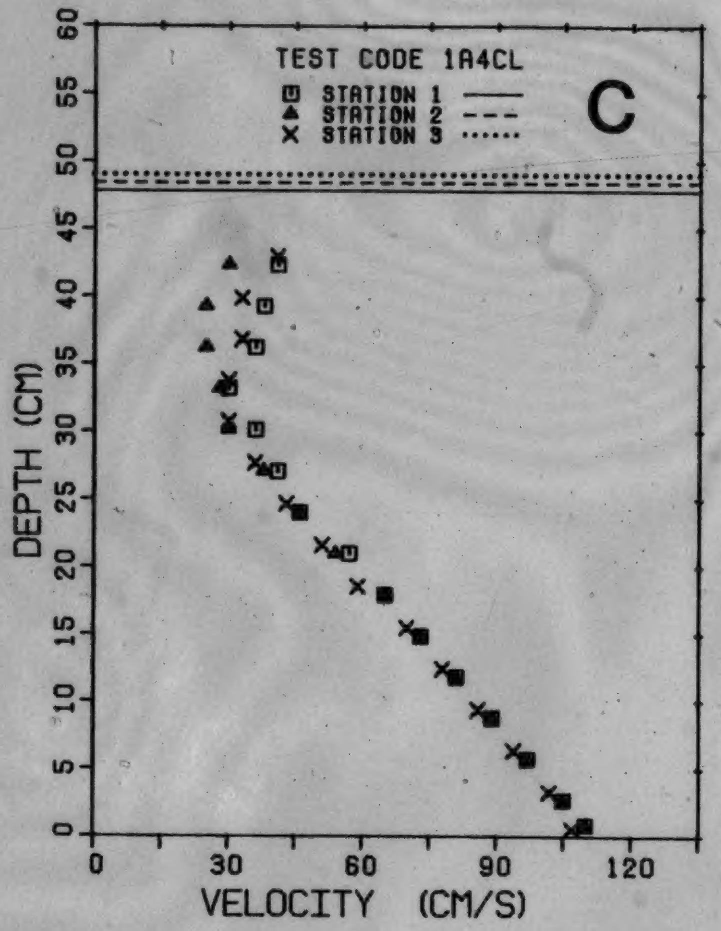
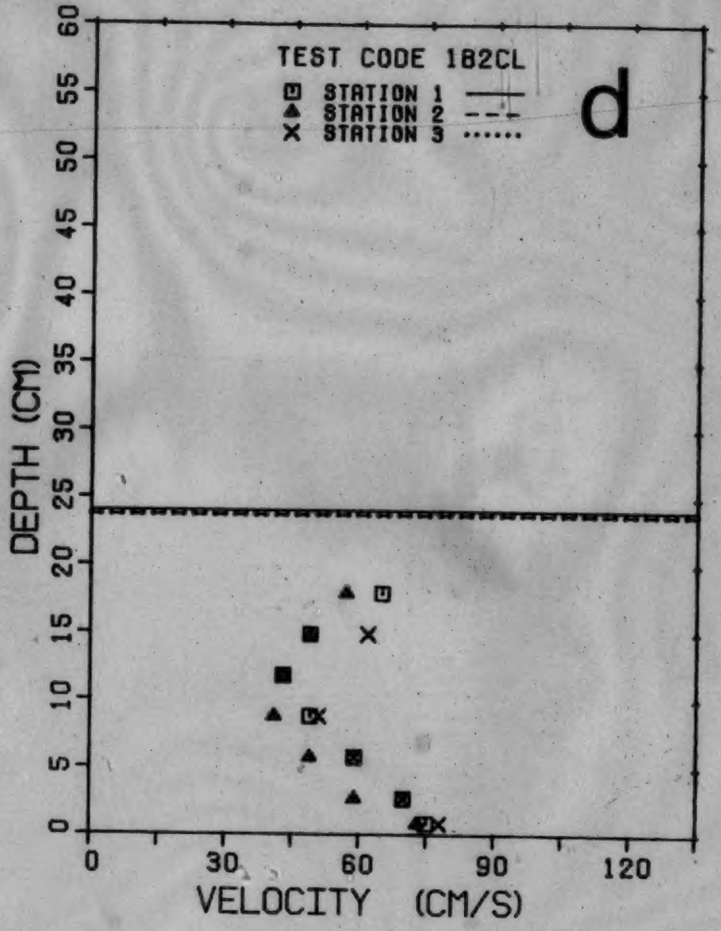
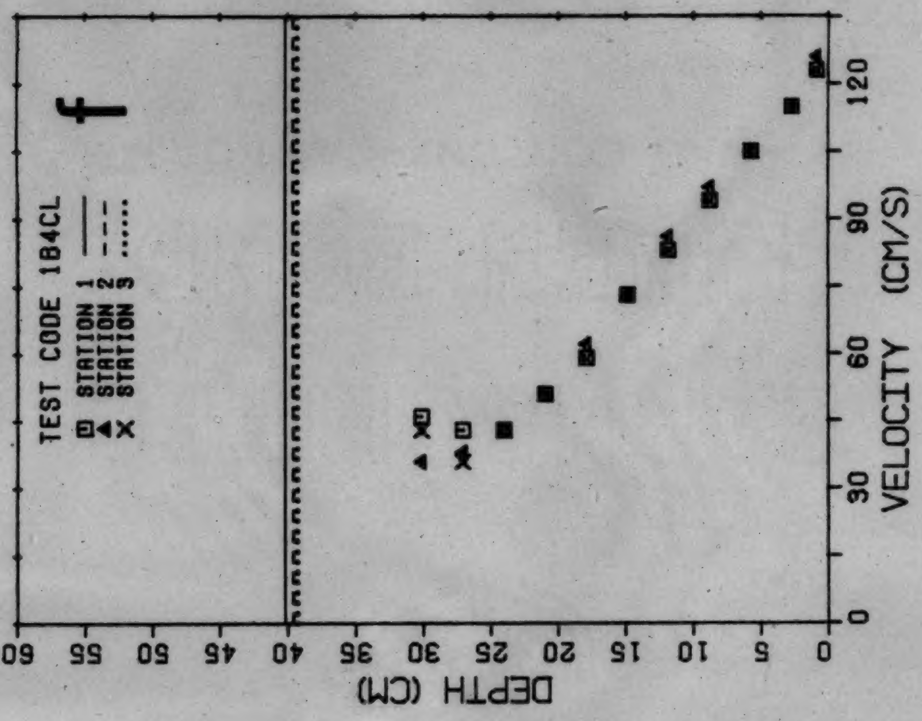
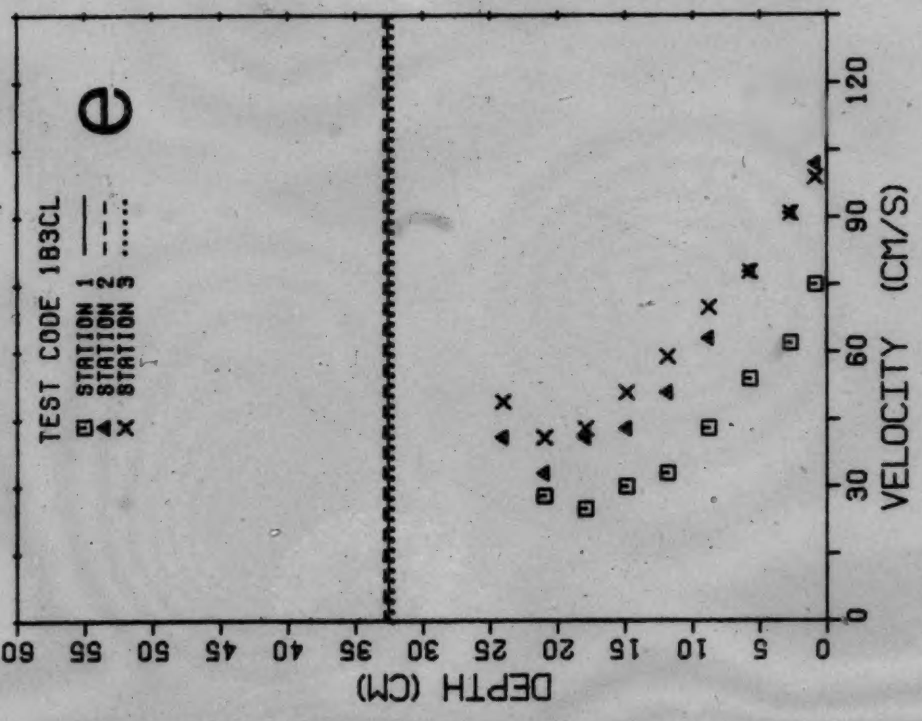


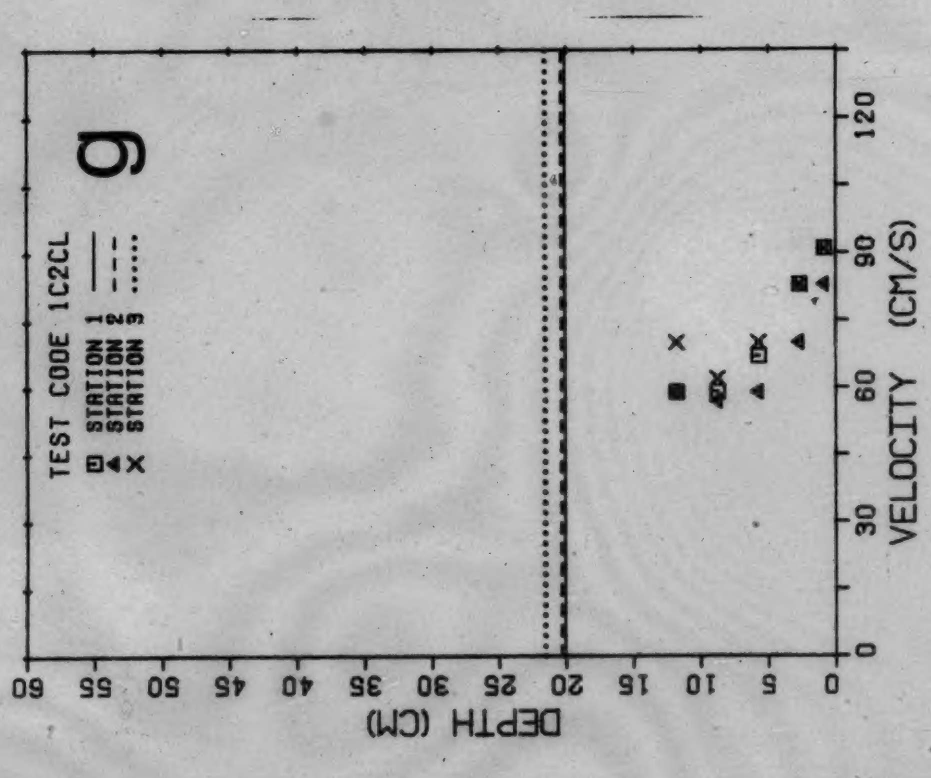
FIG. 14. Denil 1: velocity profiles at central normals

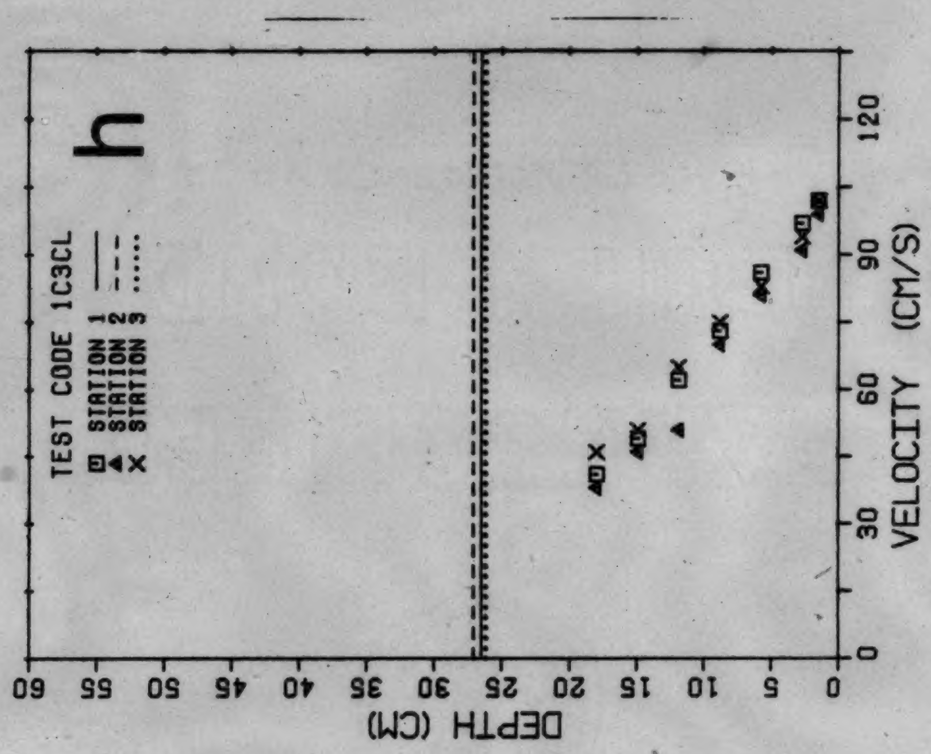

TEST CODE 1A4CL
STATION 1
STATION 2
STATION 3
c
DEPTH (CM)
0
5
10
15
20
25
30
35
40
45
50
55
60
VELOCITY (CM/S)
0
30
60
90
120

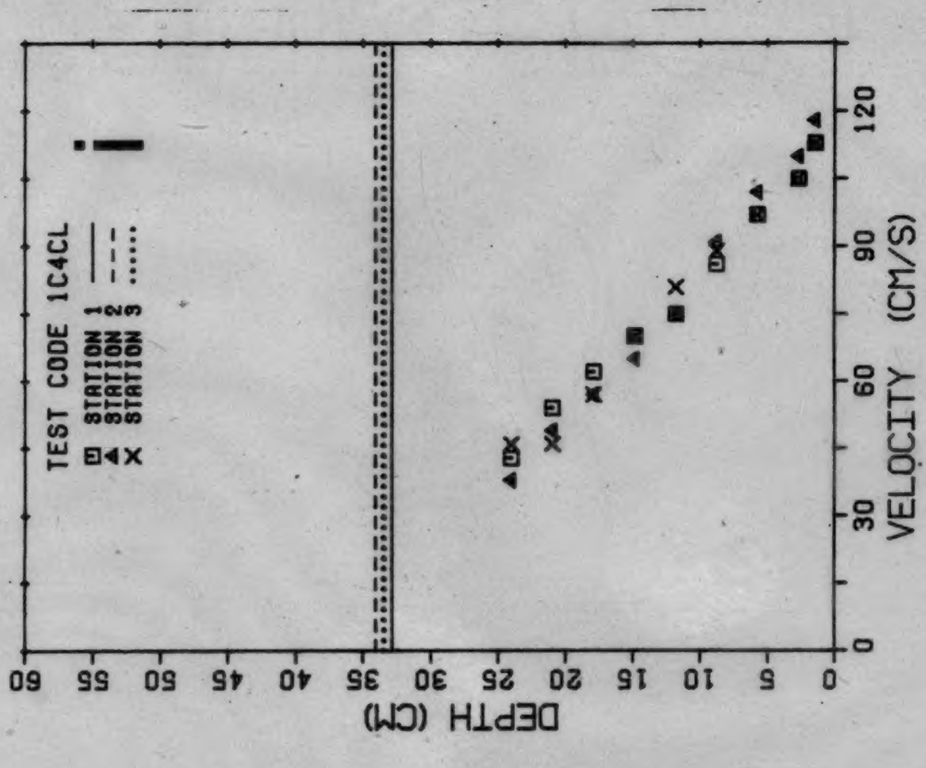

TEST CODE 1B2CL
STATION 1
STATION 2
STATION 3
d
DEPTH (CM)
0
5
10
15
20
25
30
35
40
45
50
55
60
VELOCITY (CM/S)
0
30
60
90
120


f
TEST CODE 1B4CL
⊡ STATION 1
▲ STATION 2
X STATION 3
DEPTH (CM)
0
5
10
15
20
25
30
35
40
45
50
55
60
VELOCITY (CM/S)
0
30
60
90
120


e
TEST CODE 1B3CL
⊡ STATION 1
▲ STATION 2
X STATION 3
DEPTH (CM)
0
5
10
15
20
25
30
35
40
45
50
55
60
VELOCITY (CM/S)
0
30
60
90
120


g
TEST CODE 1C2CL
STATION 1
STATION 2
STATION 3
DEPTH (CM)
VELOCITY (CM/S)
0
5
10
15
20
25
30
35
40
45
50
55
60
0
30
60
90
120


h
TEST CODE 1C3CL
STATION 1
STATION 2
STATION 3
DEPTH (CM)
VELOCITY (CM/S)
0
5
10
15
20
25
30
35
40
45
50
55
60
0
30
60
90
120


TEST CODE 1C4CL
STATION 1
STATION 2
STATION 3
DEPTH (CM)
0
5
10
15
20
25
30
35
40
45
50
55
60
VELOCITY (CM/S)
0
30
60
90
120

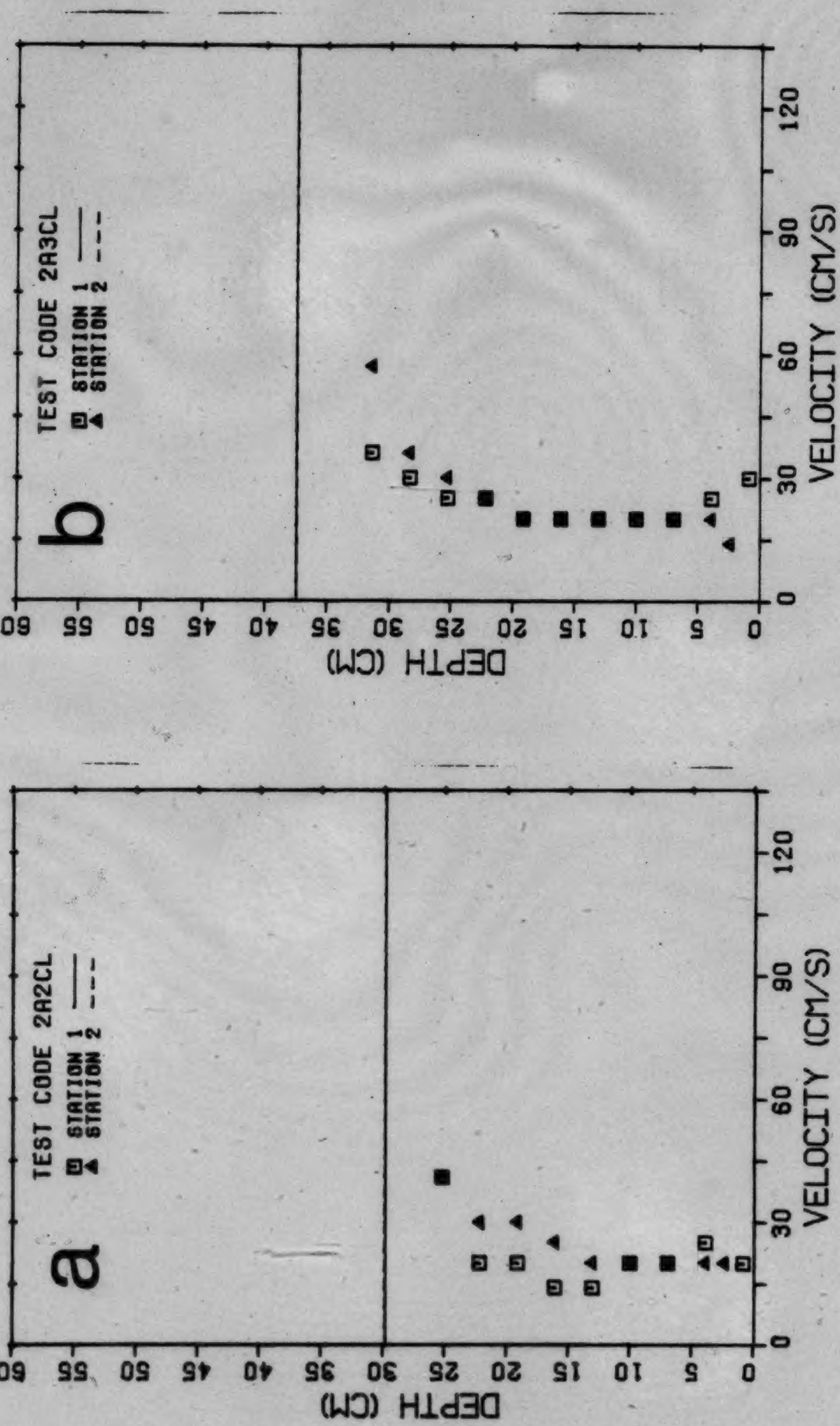
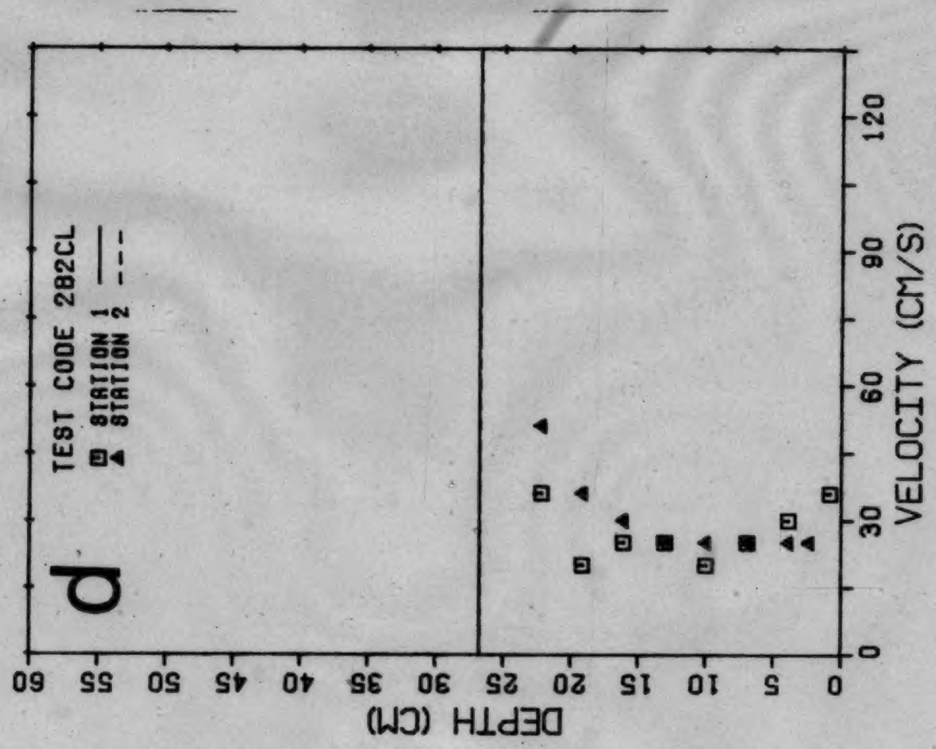
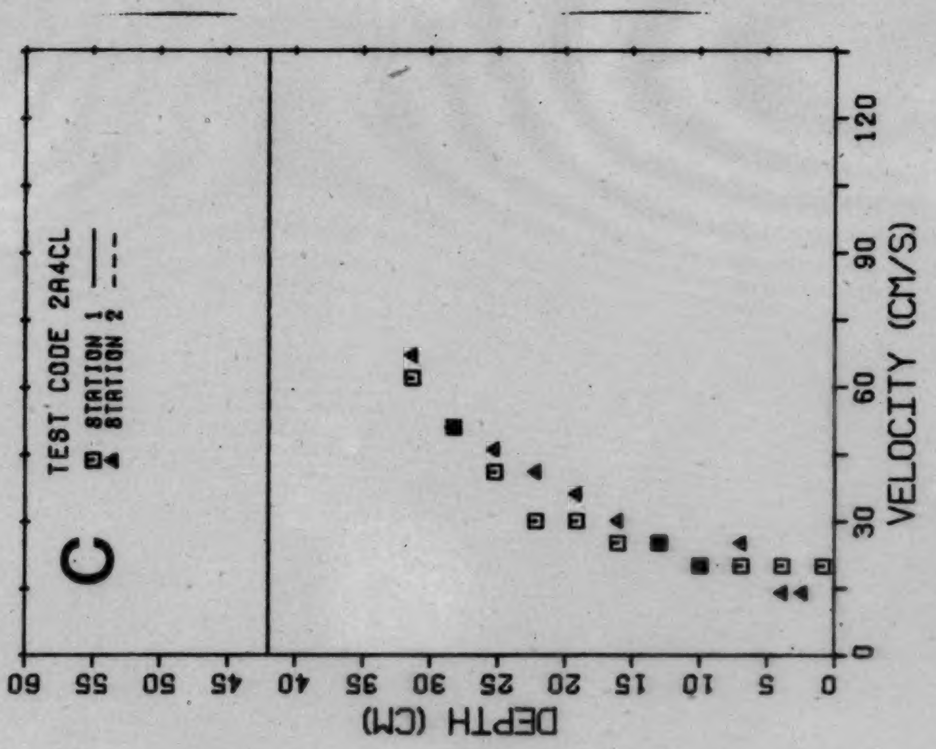
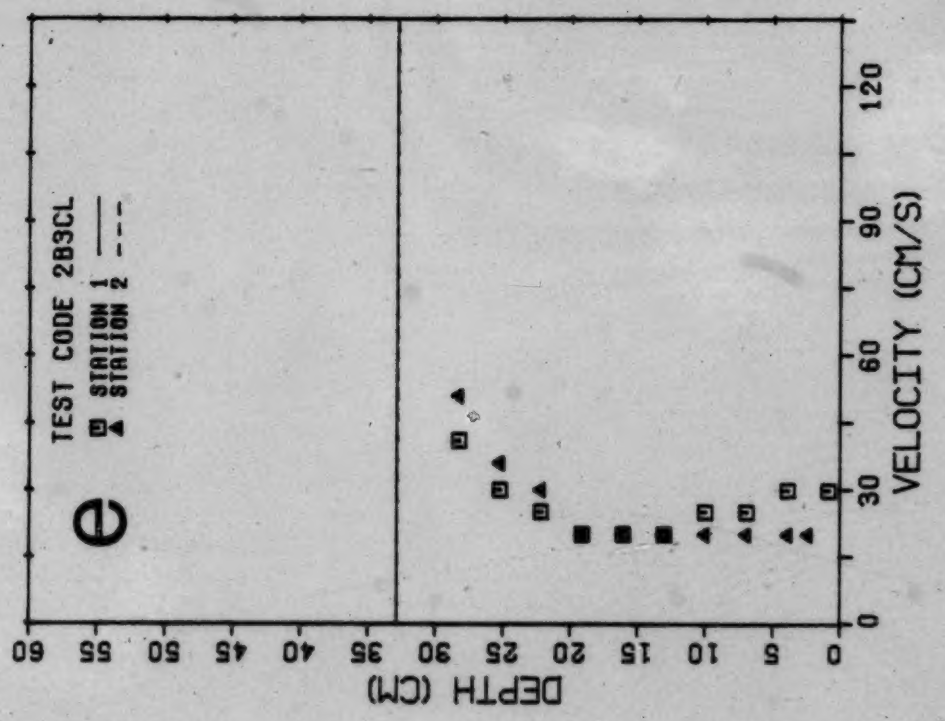
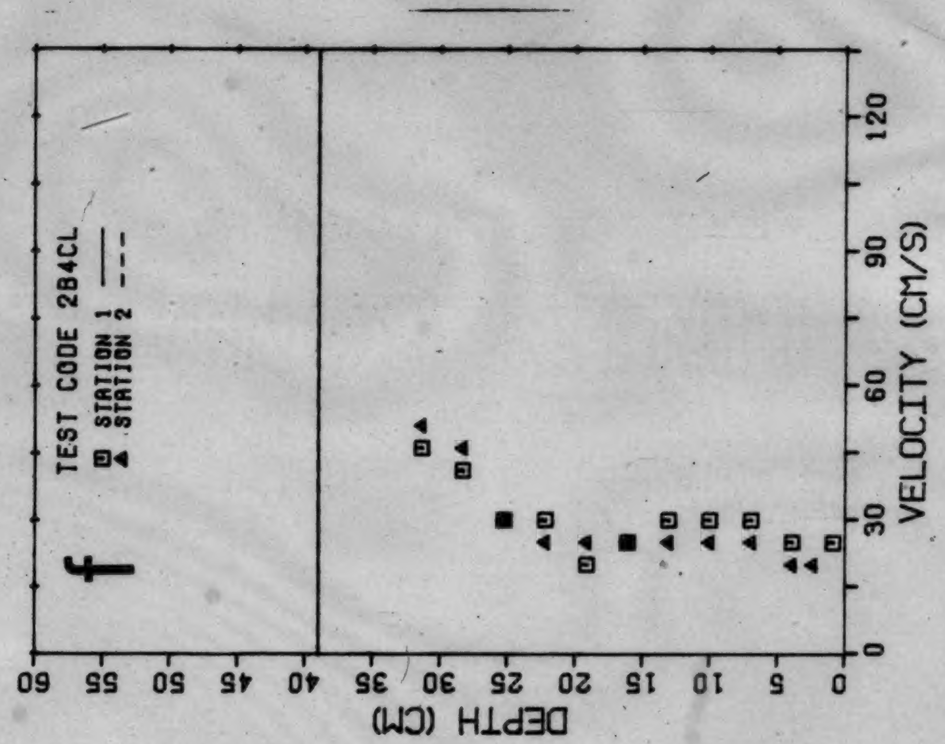


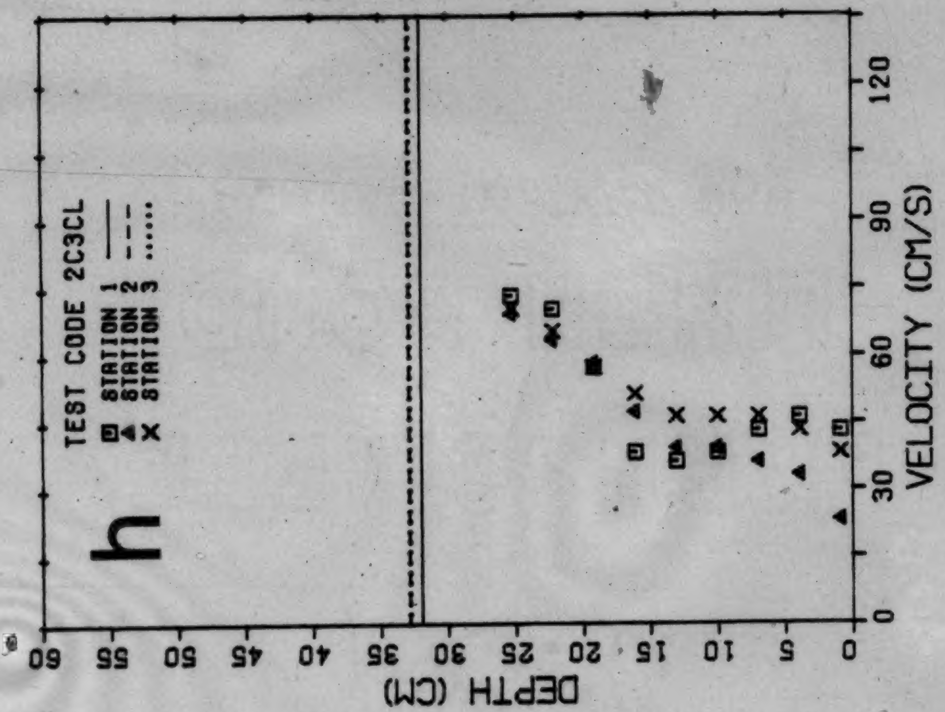
FIG. 15. Denil 2: velocity profiles at central normals.

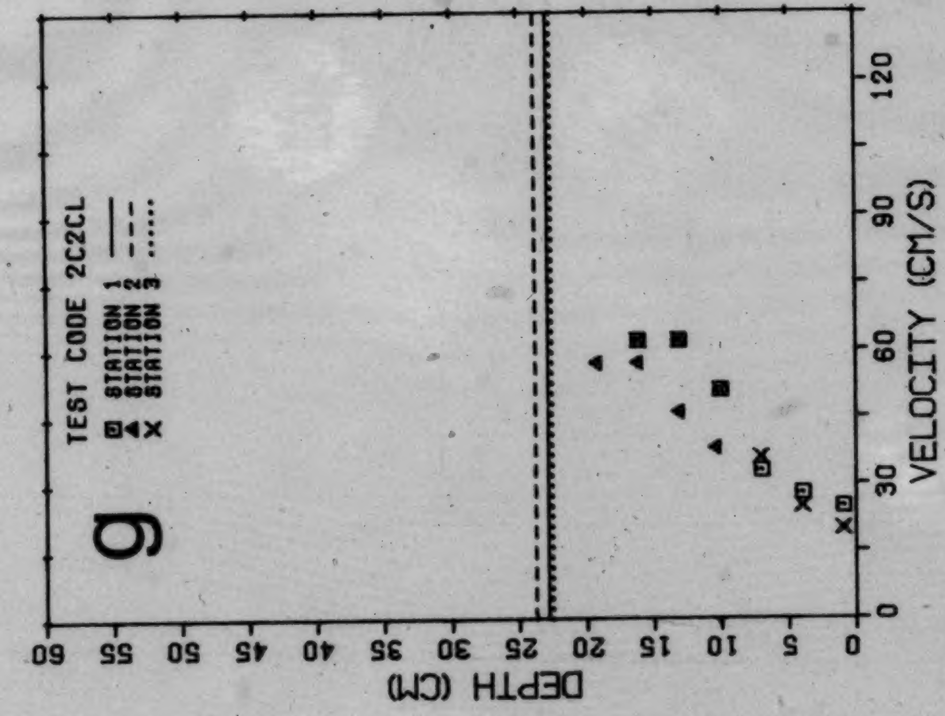

d
TEST CODE 2B2CL
⊡ STATION 1 ———
▲ STATION 2 - - -
DEPTH (CM)
0
5
10
15
20
25
30
35
40
45
50
55
60
VELOCITY (CM/S)
0
30
60
90
120

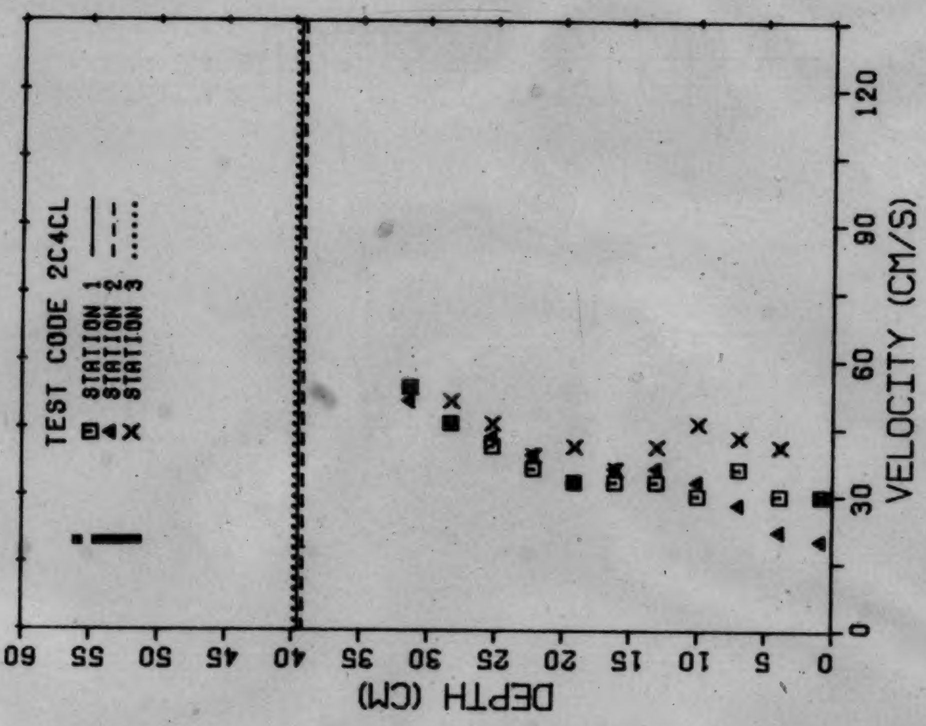

C
TEST CODE 2A4CL
⊡ STATION 1 ———
▲ STATION 2 - - -
DEPTH (CM)
0
5
10
15
20
25
30
35
40
45
50
55
60
VELOCITY (CM/S)
0
30
60
90
120


e
TEST CODE 2B3CL
⊡ STATION 1 ——
▲ STATION 2 - - -
DEPTH (CM)
0
5
10
15
20
25
30
35
40
45
50
55
60
VELOCITY (CM/S)
0
30
60
90
120


f
TEST CODE 2B4CL
⊡ STATION 1 ——
▲ STATION 2 - - -
DEPTH (CM)
0
5
10
15
20
25
30
35
40
45
50
55
60
VELOCITY (CM/S)
0
30
60
90
120


h
TEST CODE 2C3CL
STATION 1
STATION 2
STATION 3
DEPTH (CM)
0
5
10
15
20
25
30
35
40
45
50
55
60
VELOCITY (CM/S)
0
30
60
90
120


g
TEST CODE 2C2CL
STATION 1
STATION 2
STATION 3
DEPTH (CM)
0
5
10
15
20
25
30
35
40
45
50
55
60
VELOCITY (CM/S)
0
30
60
90
120


TEST CODE 2C4CL
STATION 1
STATION 2
STATION 3
VELOCITY (CM/S)
0
30
60
90
120
DEPTH (CM)
0
5
10
15
20
25
30
35
40
45
50
55
60

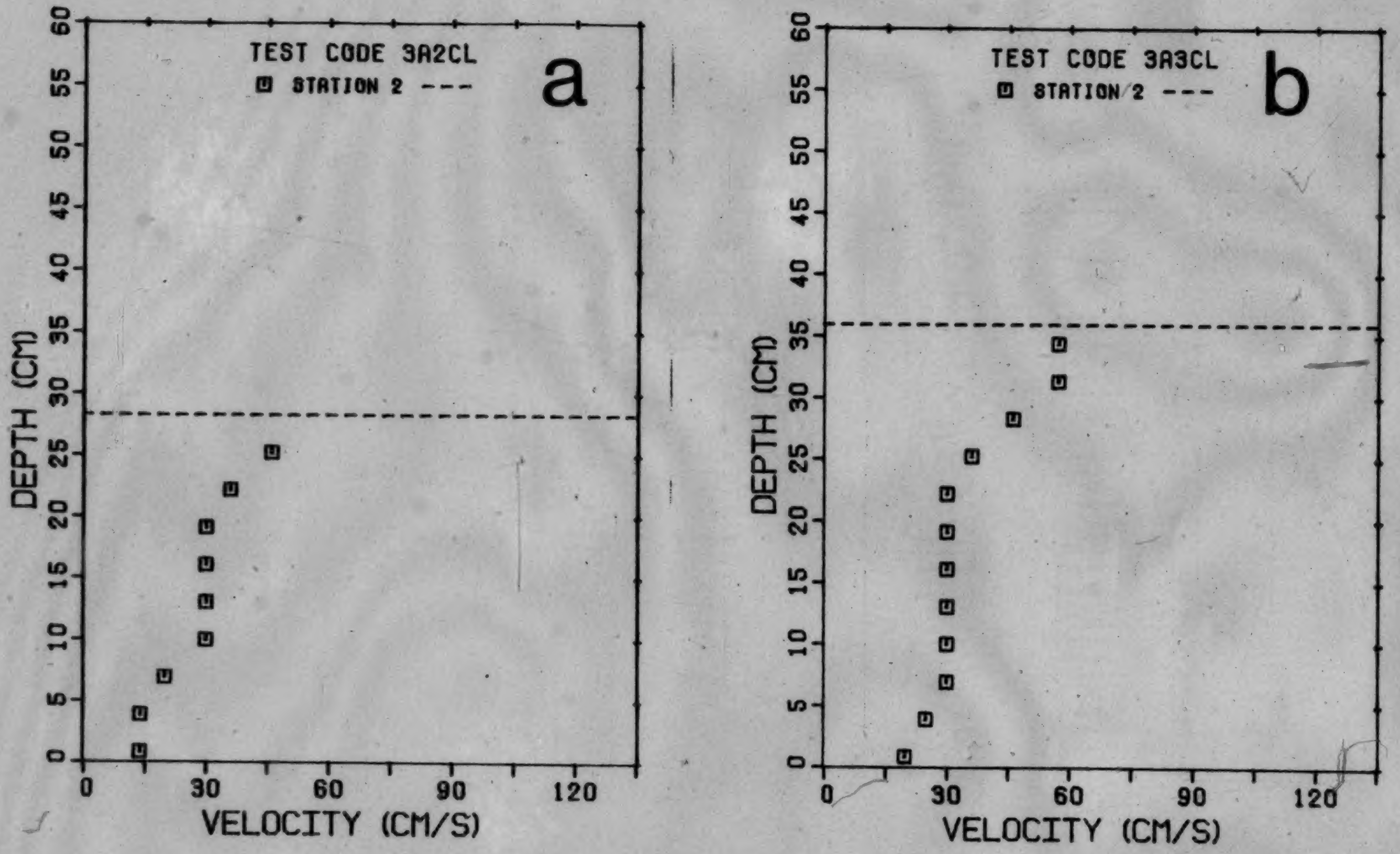
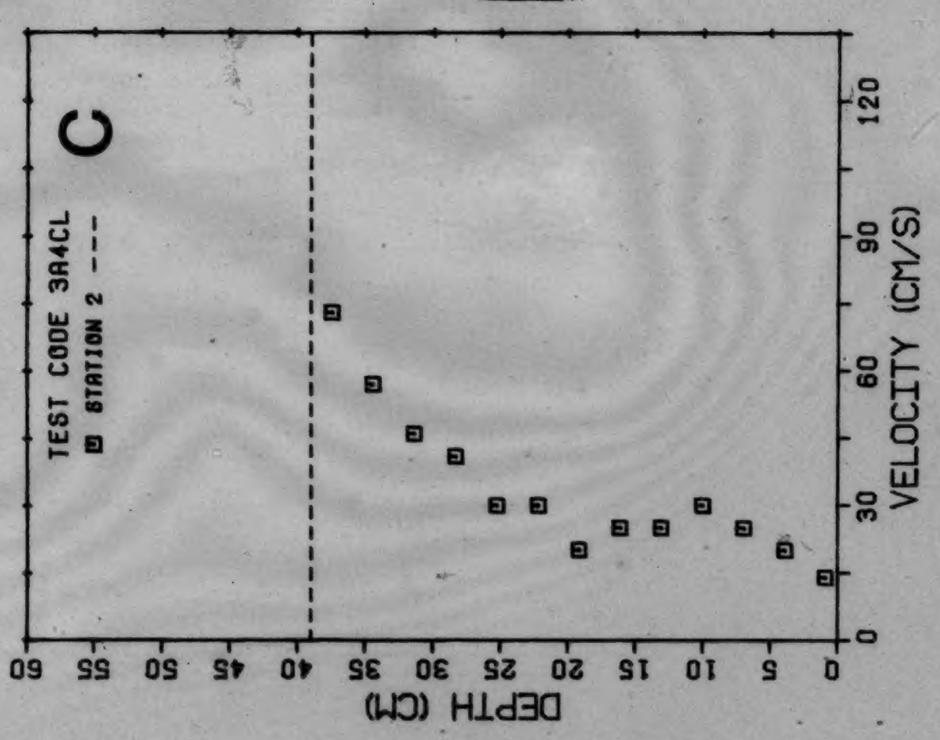
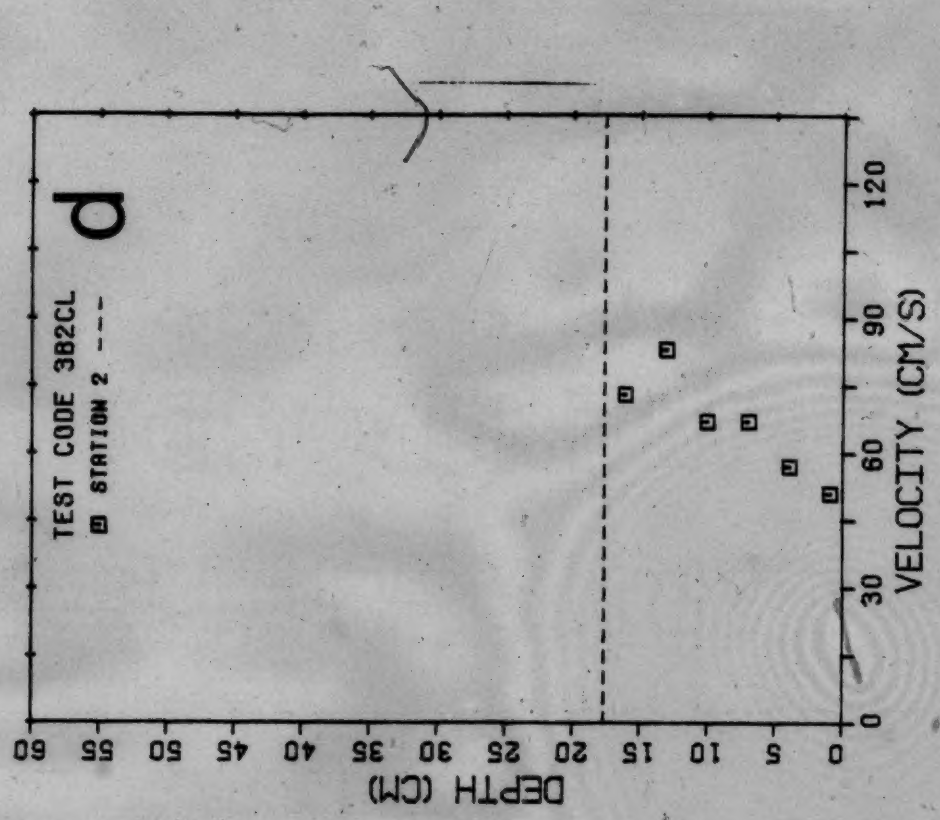
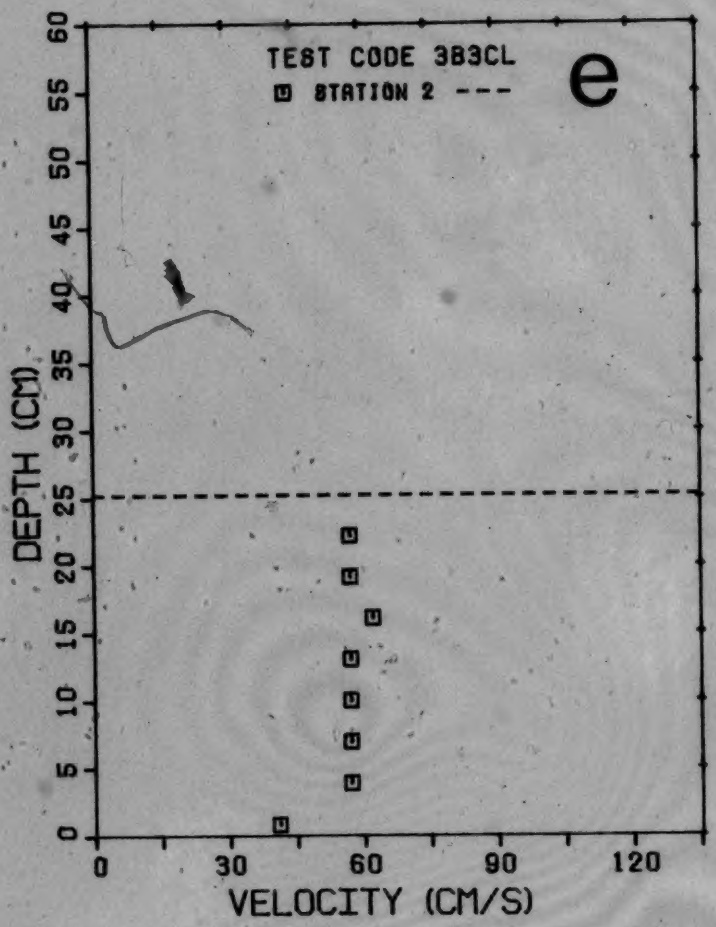
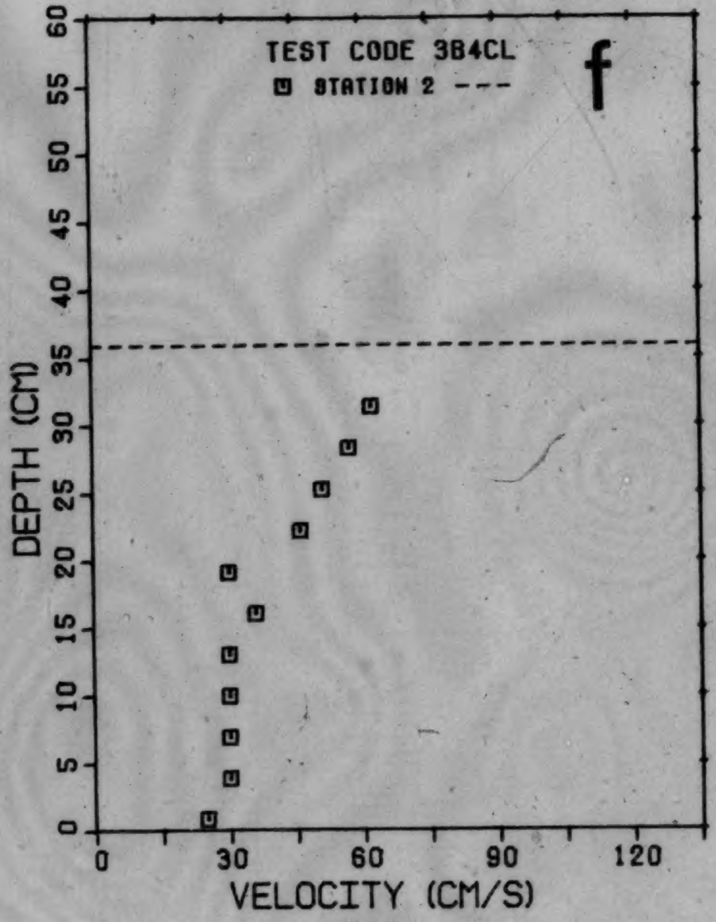


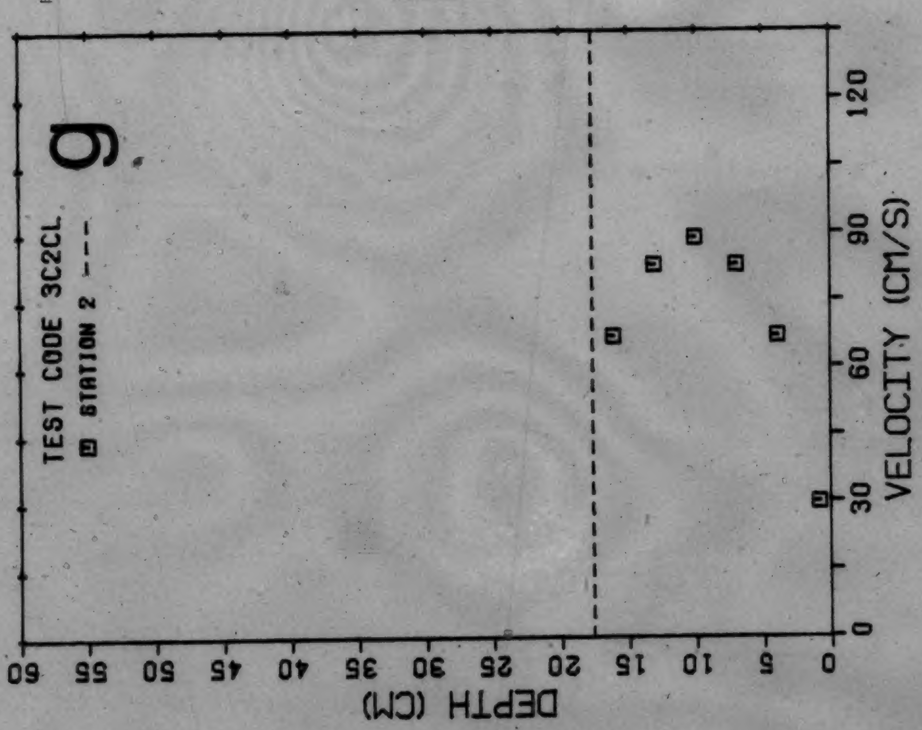
FIG. 16. Denil 3: velocity profiles at central normals.

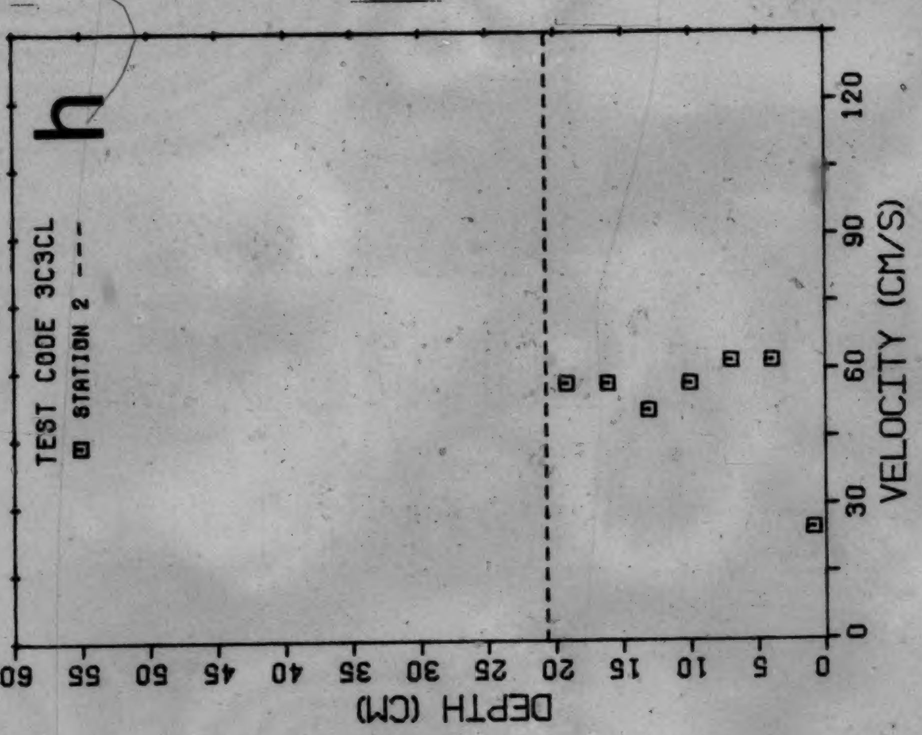

TEST CODE 3A4CL
STATION 2
C
DEPTH (CM)
VELOCITY (CM/S)
0
5
10
15
20
25
30
35
40
45
50
55
60
0
30
60
90
120

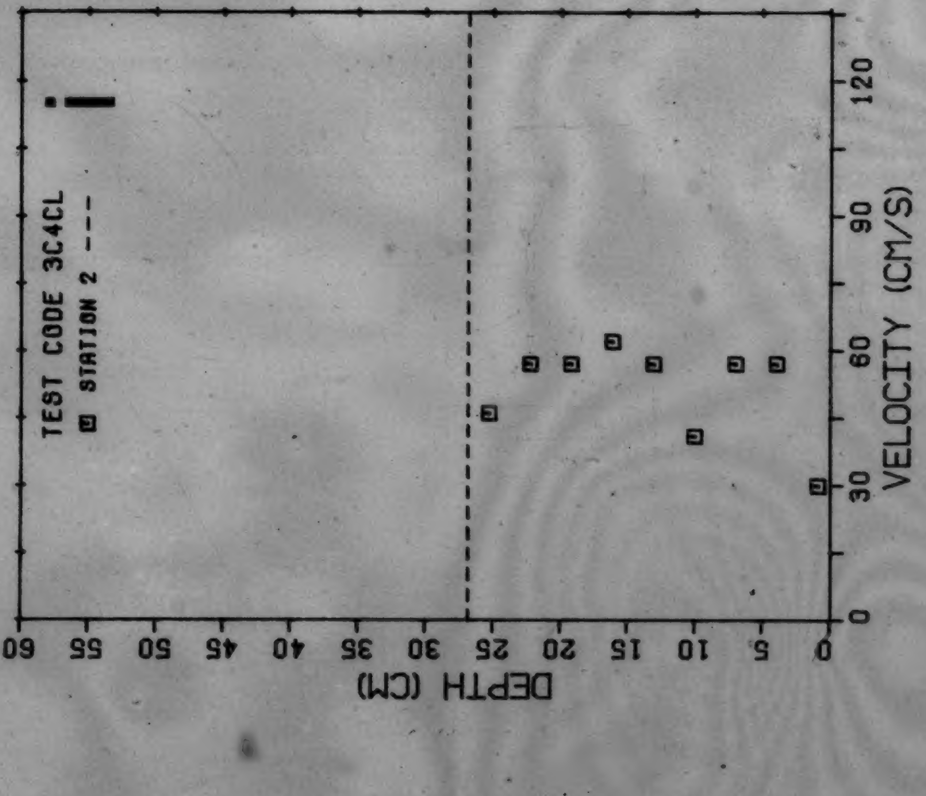

TEST CODE 3B2CL
STATION 2
d
DEPTH (CM)
VELOCITY (CM/S)
0
5
10
15
20
25
30
35
40
45
50
55
60
0
30
60
90
120

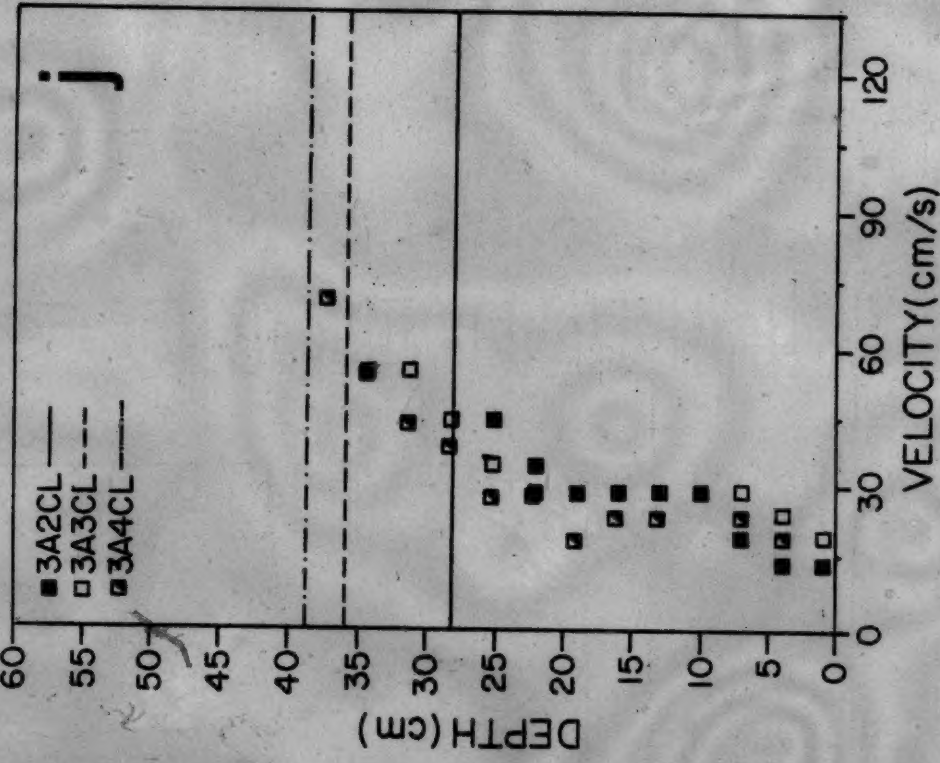

TEST CODE 3B3CL
⊡ STATION 2 ---
e
DEPTH (CM)
0
5
10
15
20
25
30
35
40
45
50
55
60
VELOCITY (CM/S)
0
30
60
90
120

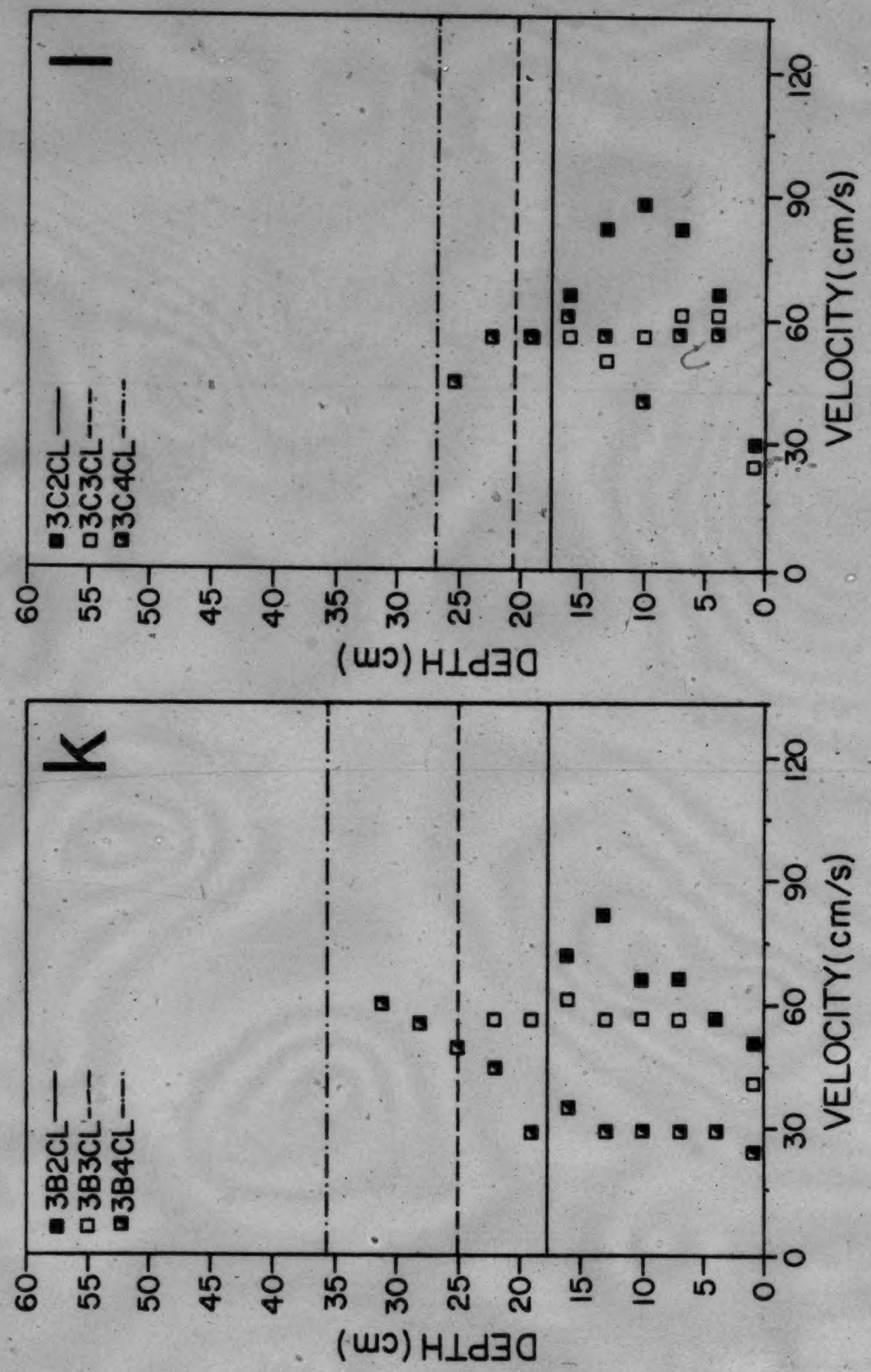

TEST CODE 3B4CL
⊡ STATION 2 ---
f
DEPTH (CM)
0
5
10
15
20
25
30
35
40
45
50
55
60
VELOCITY (CM/S)
0
30
60
90
120


g
TEST CODE 3C2CL
STATION 2 ----
DEPTH (CM)
0
5
10
15
20
25
30
35
40
45
50
55
60
VELOCITY (CM/S)
0
30
60
90
120


h
TEST CODE 3C3CL
STATION 2 ----
DEPTH (CM)
0
5
10
15
20
25
30
35
40
45
50
55
60
VELOCITY (CM/S)
0
30
60
90
120


i
TEST CODE 3C4CL
STATION 2 ----
DEPTH (CM)
0
5
10
15
20
25
30
35
40
45
50
55
60
VELOCITY (CM/S)
0
30
60
90
120


j
3A2CL ——
3A3CL - - -
3A4CL -·-·-
DEPTH (cm)
0
5
10
15
20
25
30
35
40
45
50
55
60
VELOCITY(cm/s)
0
30
60
90
120


l
■ 3C2CL —
□ 3C3CL ---
▣ 3C4CL -·-
DEPTH (cm)
60
55
50
45
40
35
30
25
20
15
10
5
0
VELOCITY(cm/s)
0
30
60
90
120
k
■ 3B2CL —
□ 3B3CL ---
▣ 3B4CL -·-
DEPTH (cm)
60
55
50
45
40
35
30
25
20
15
10
5
0
VELOCITY(cm/s)
0
30
60
90
120

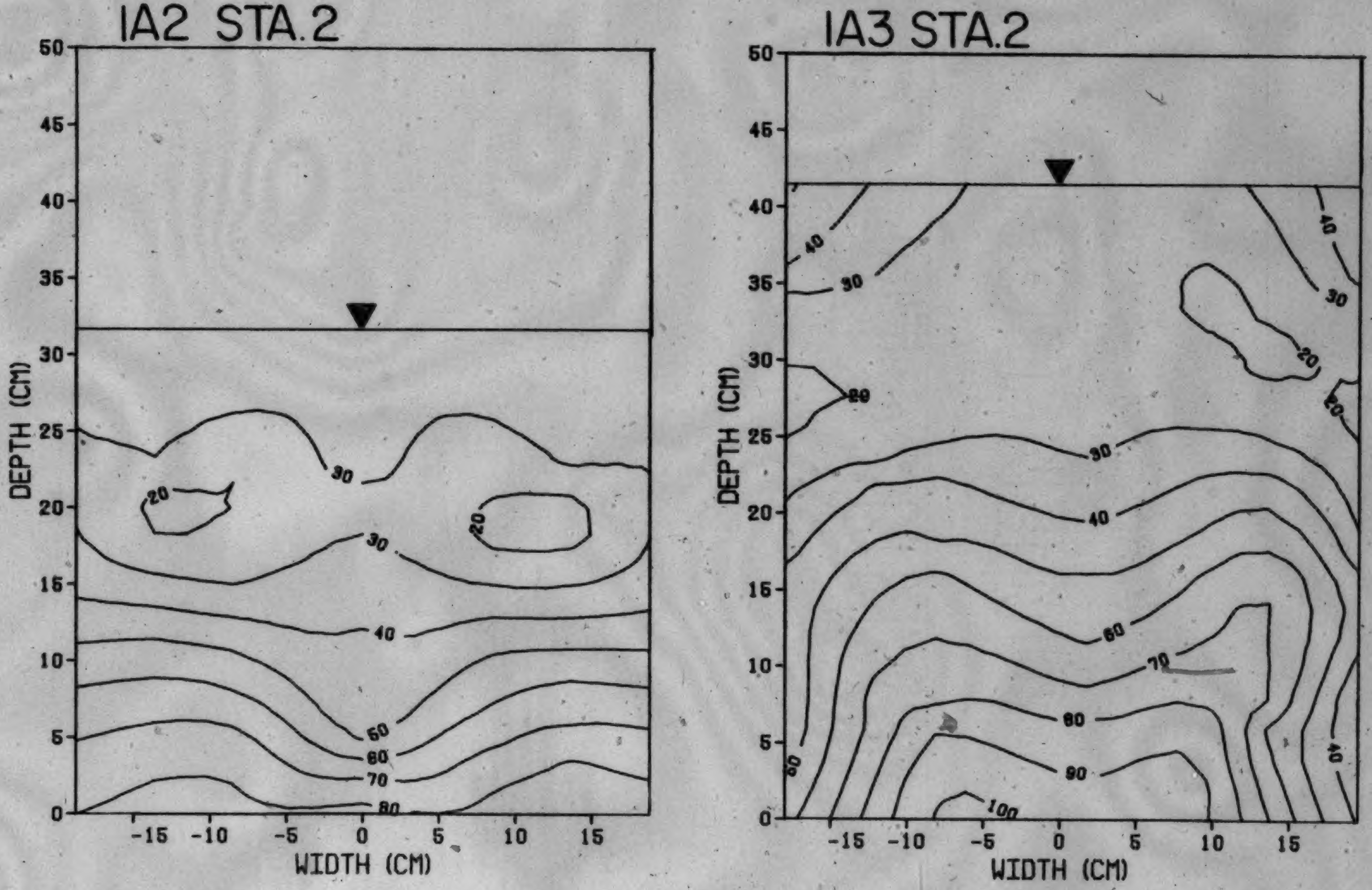
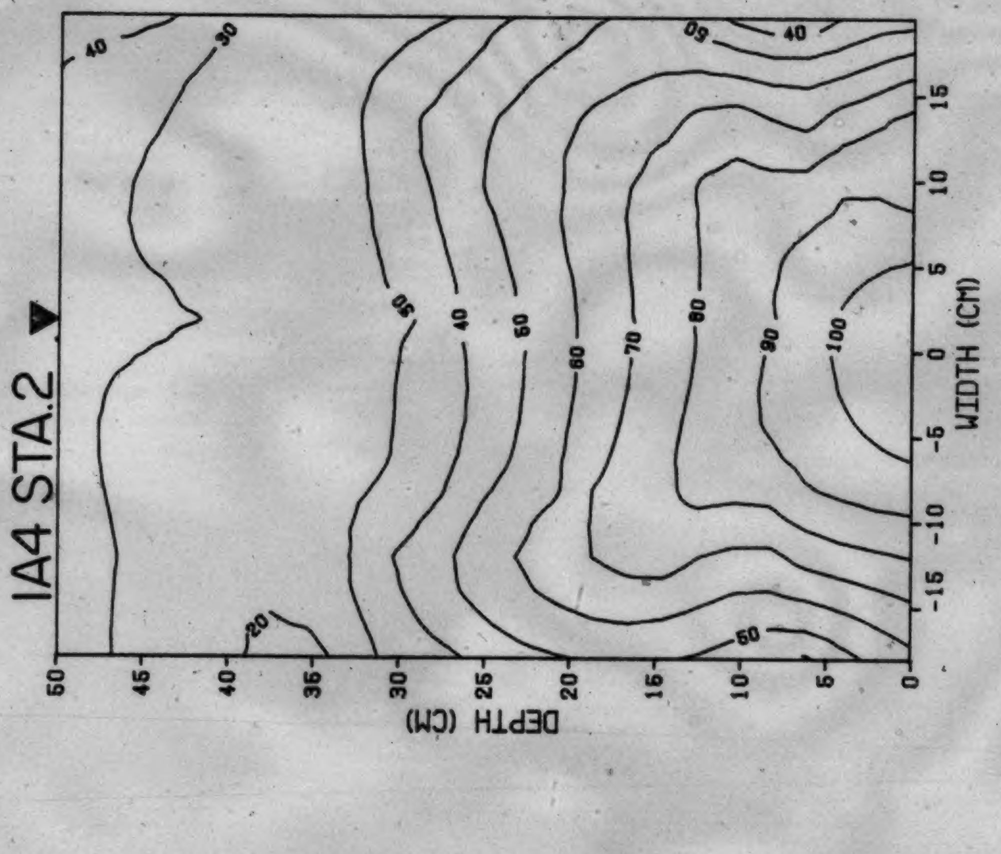
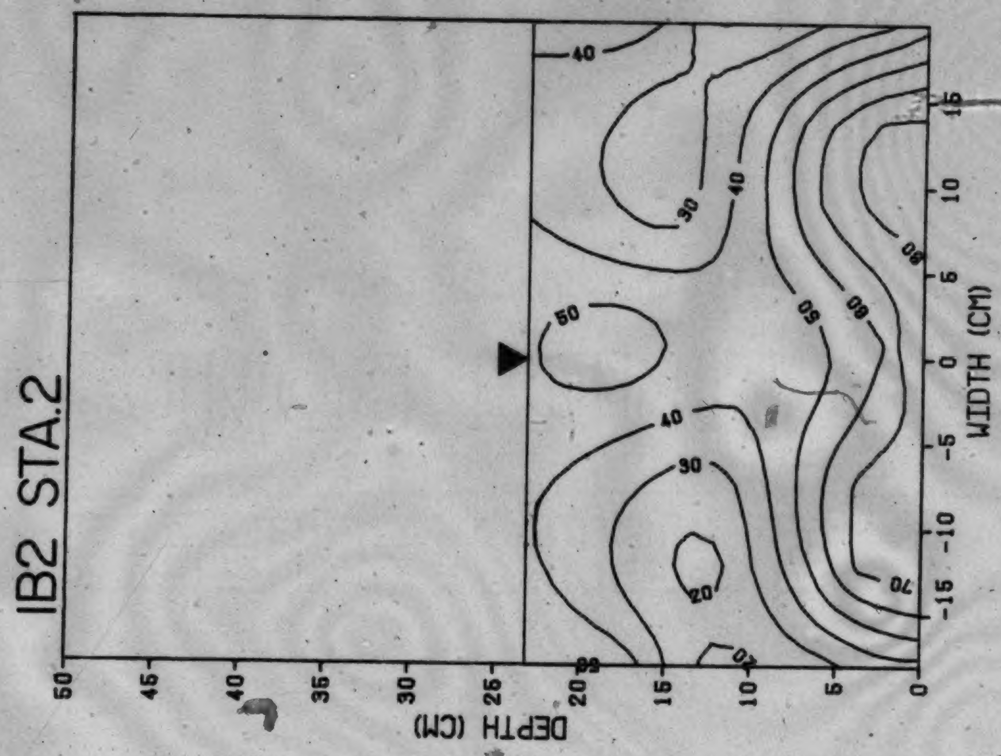


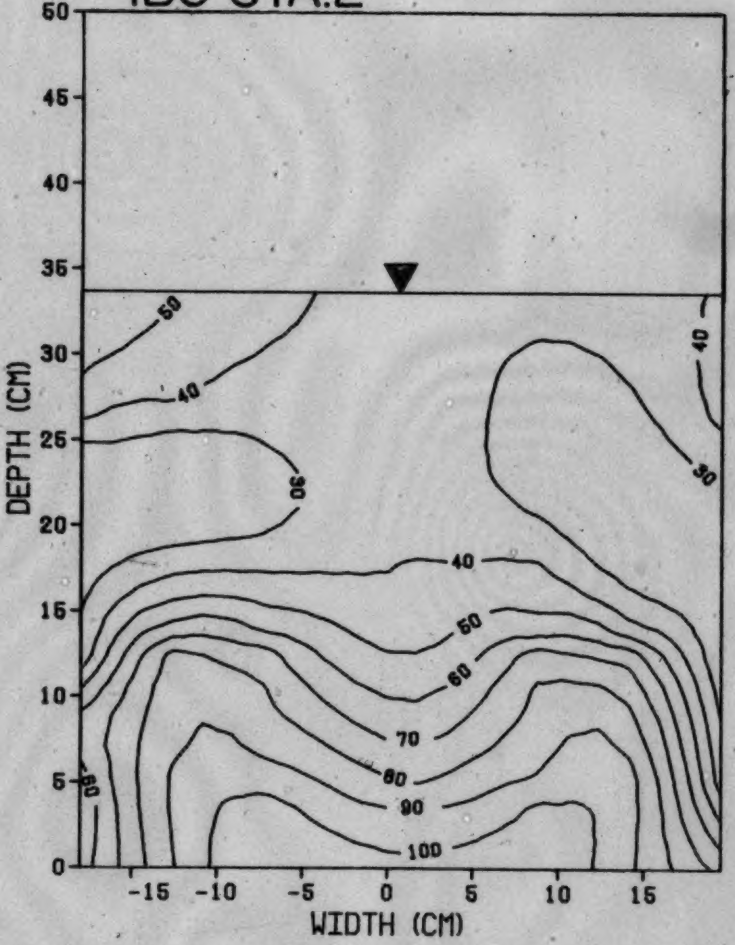
FIG. 17. Denil 1: velocity contours

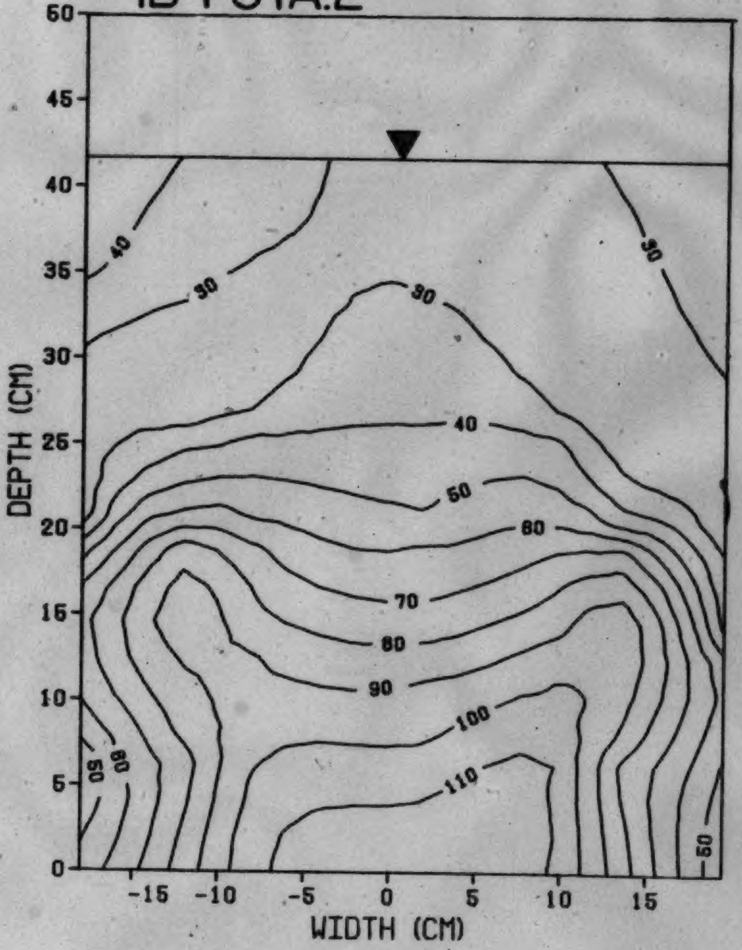


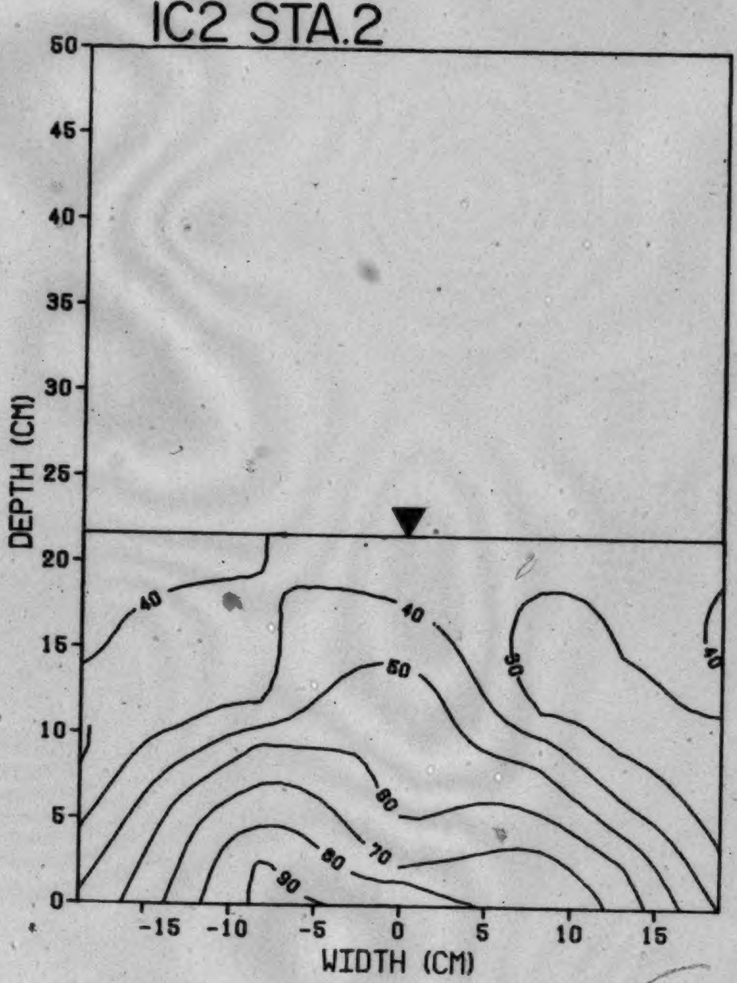
IA4 STA.2



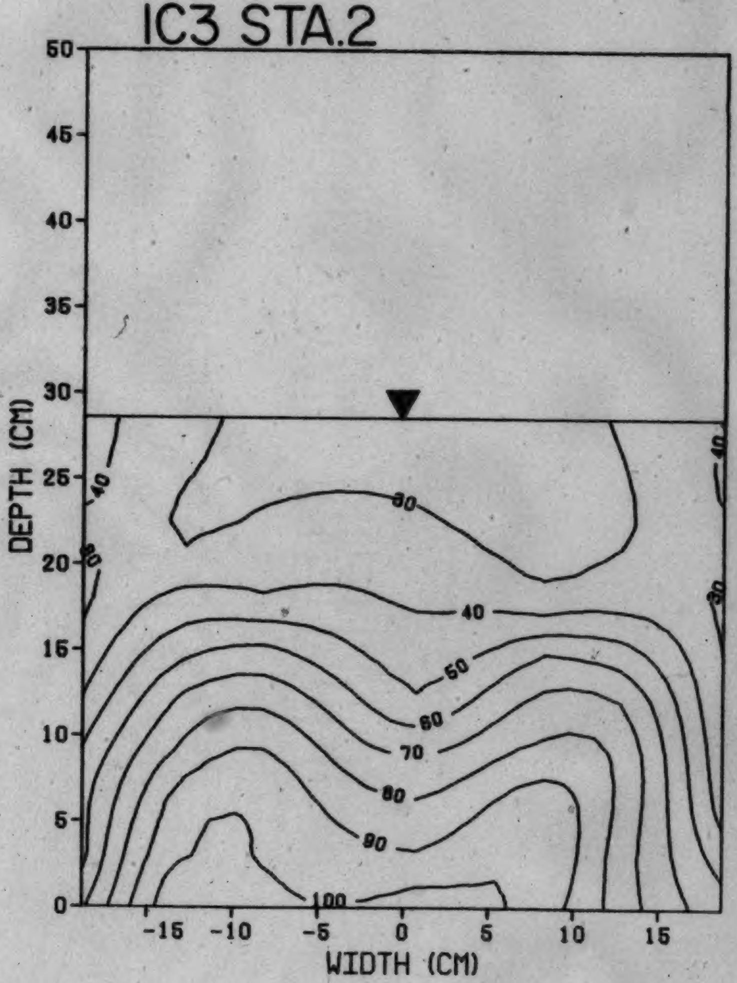
IB2 STA.2


IB3 STA.2


IB4 STA.2

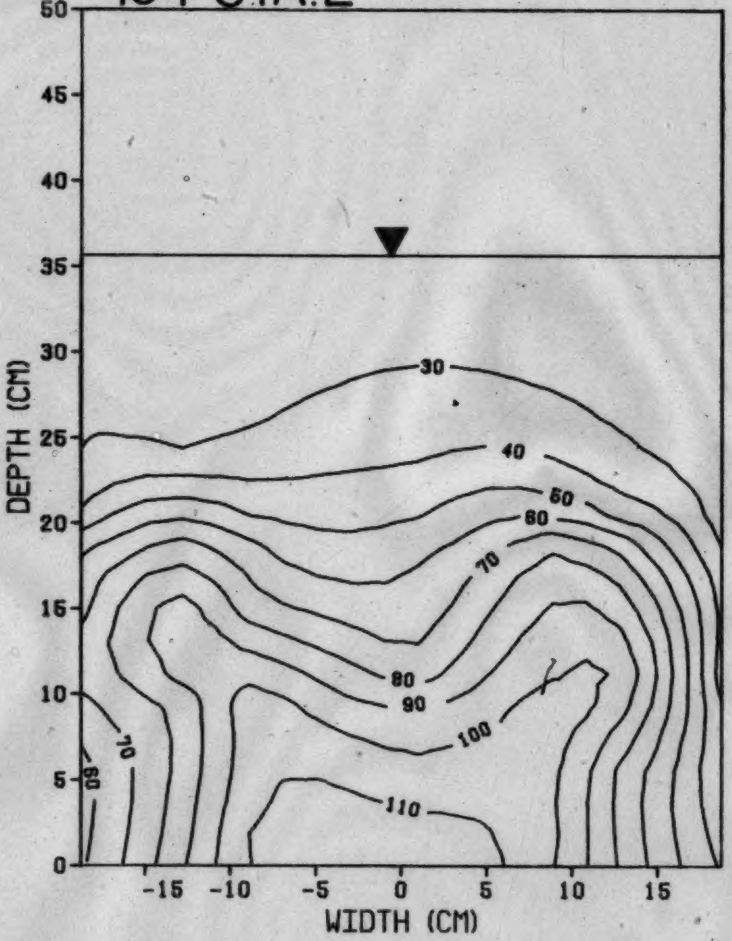


IC2 STA.2

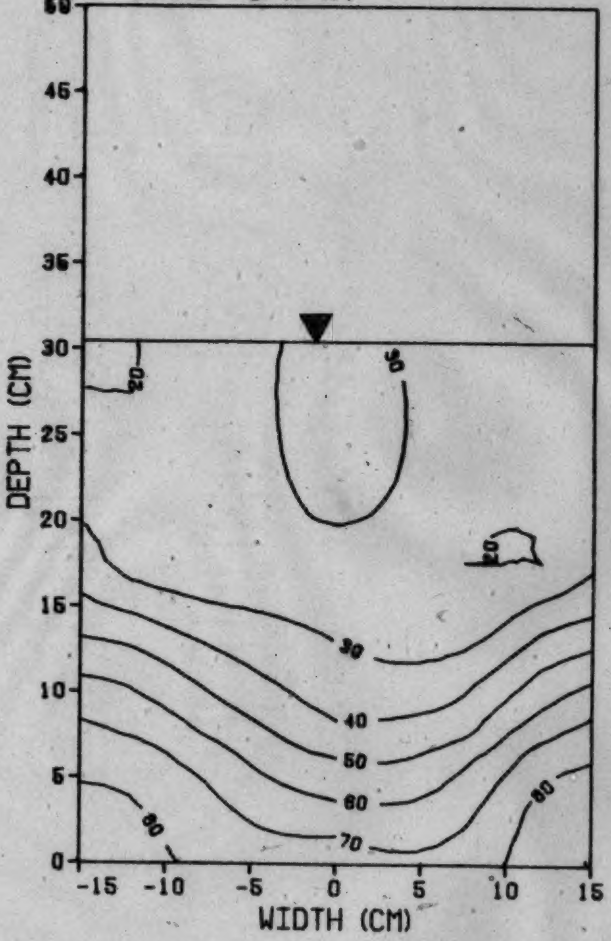


IC3 STA.2

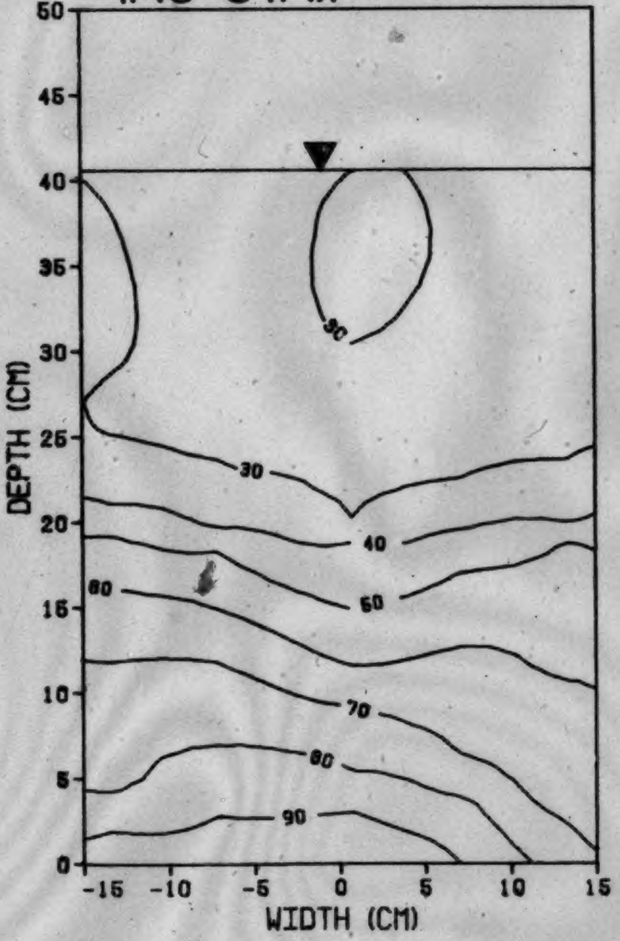
IC4 STA.2



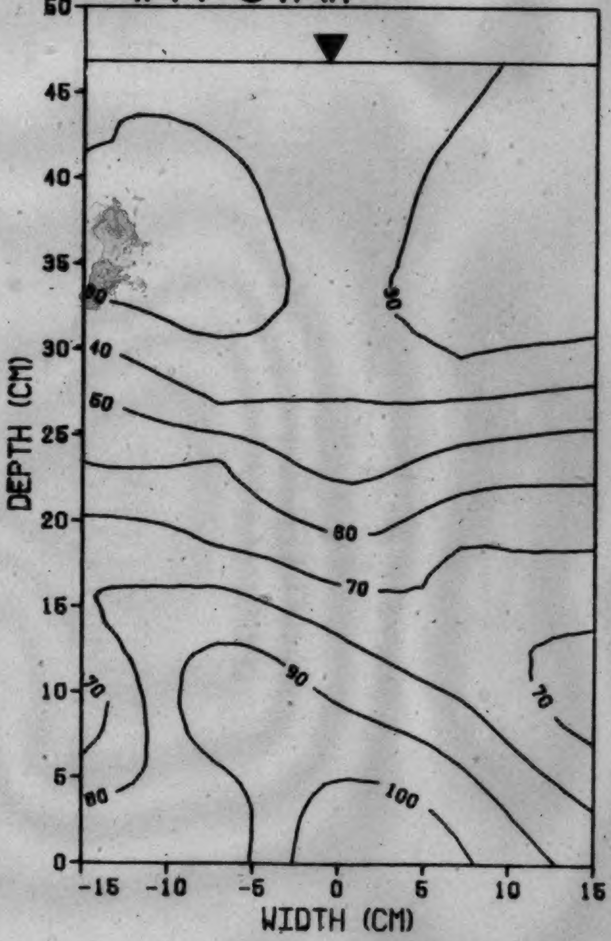
IA2 STA.1



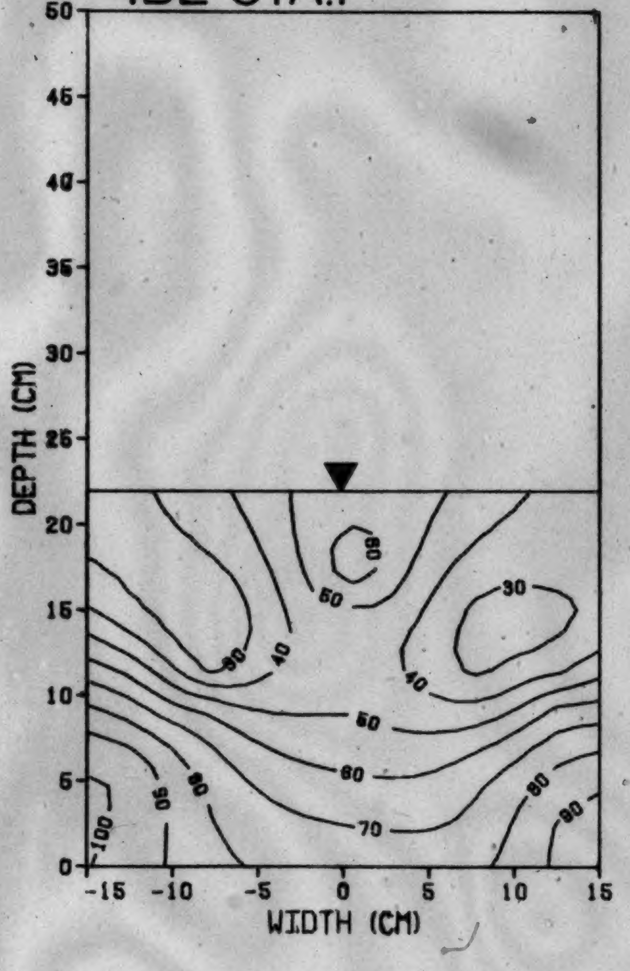
IA3 STA.I



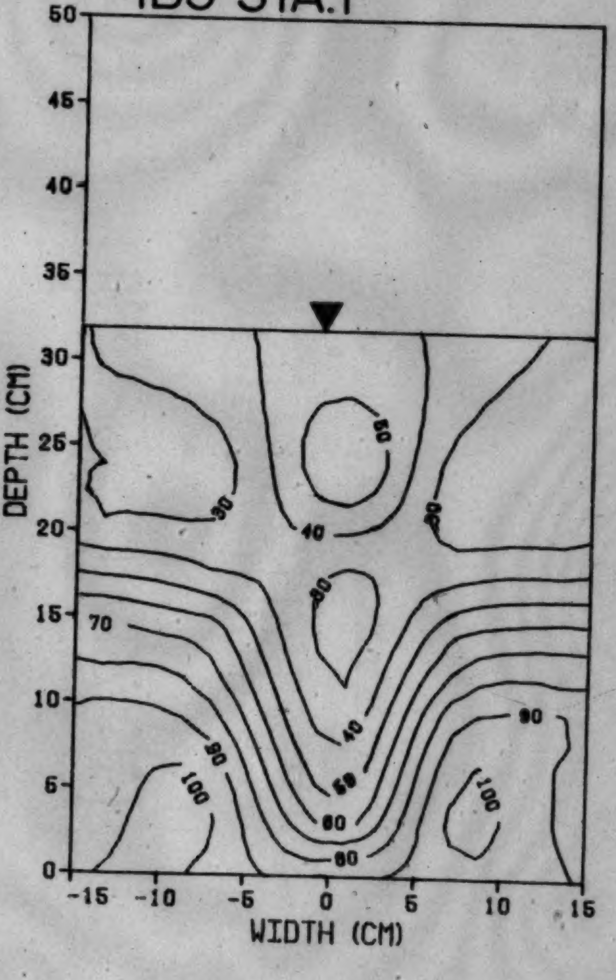
IA4 STA.I

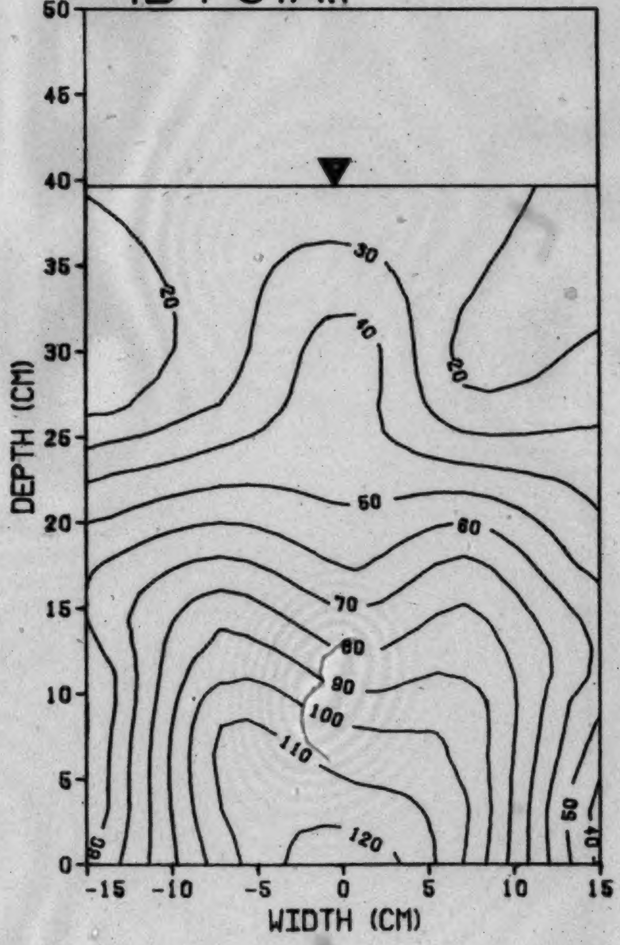


IB2 STA.I

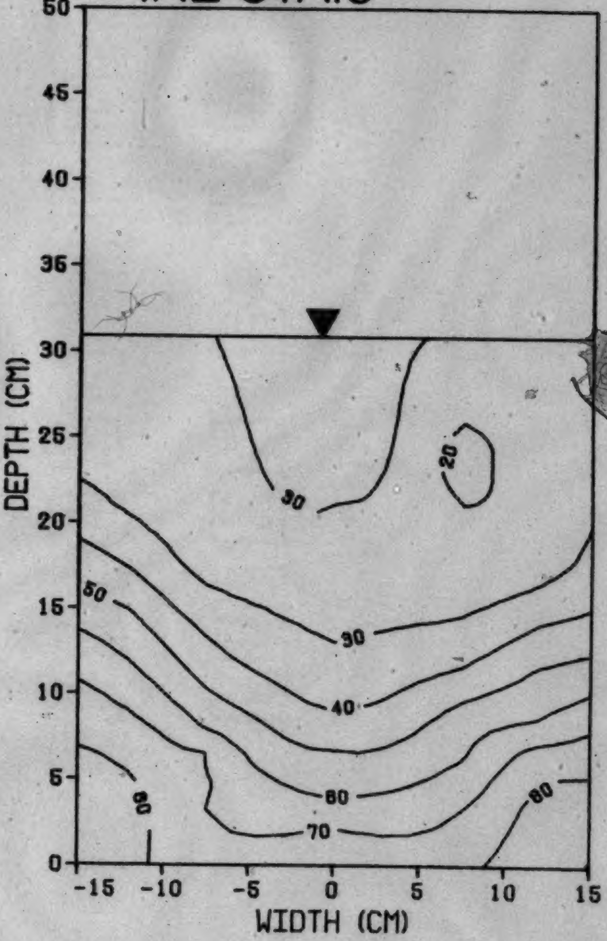


IB3 STA.I

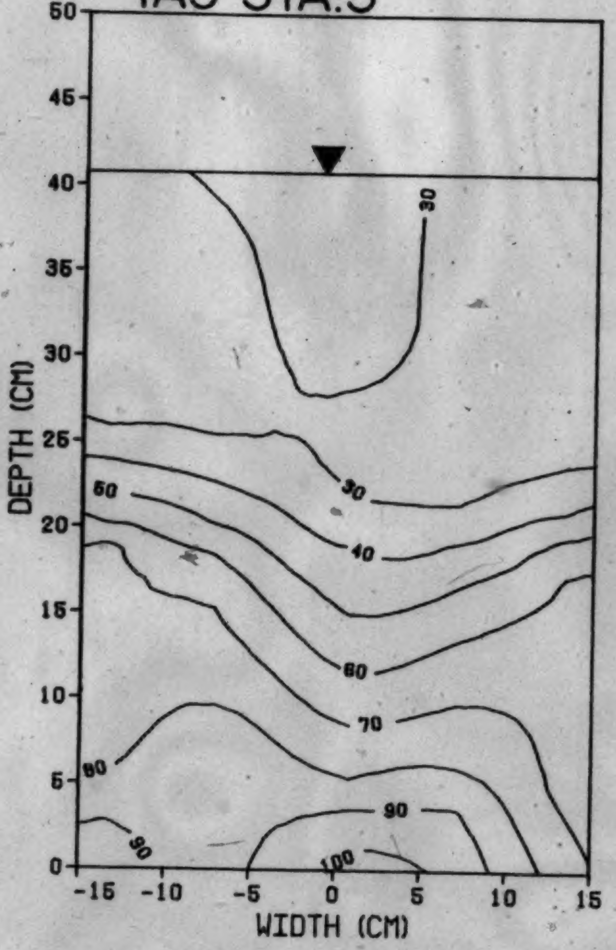




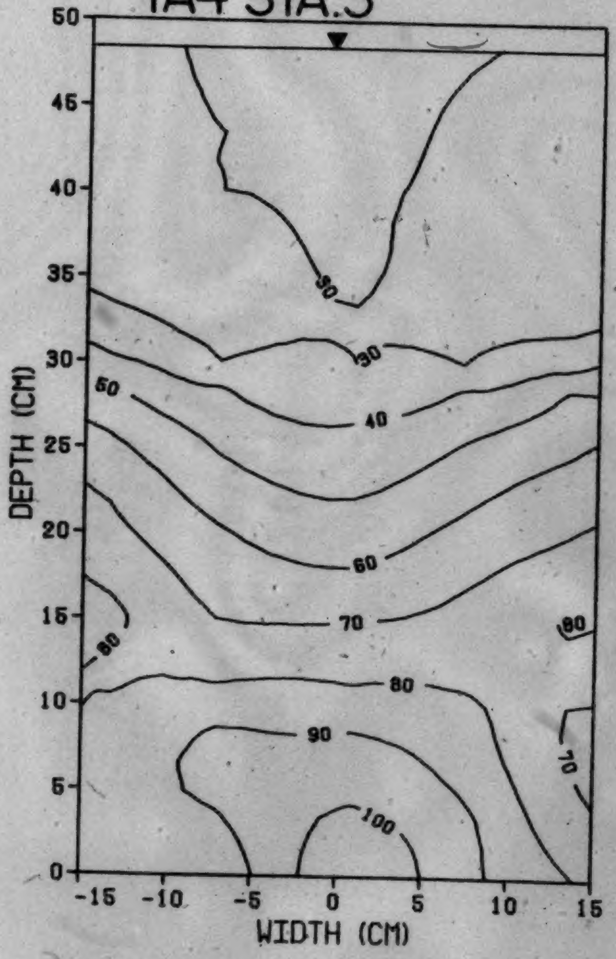
IB4 STA.1



IA2 STA.3

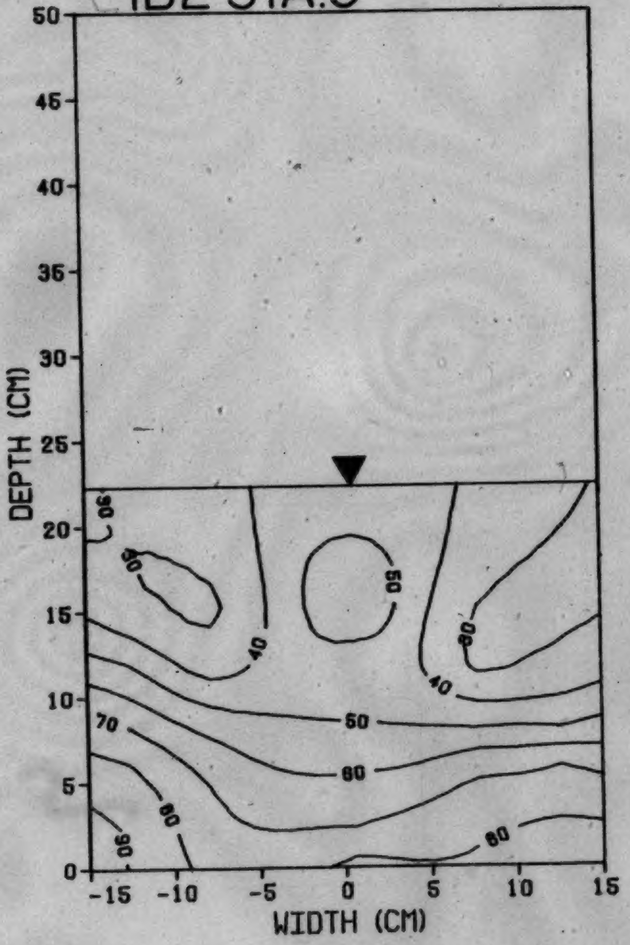


IA3 STA.3

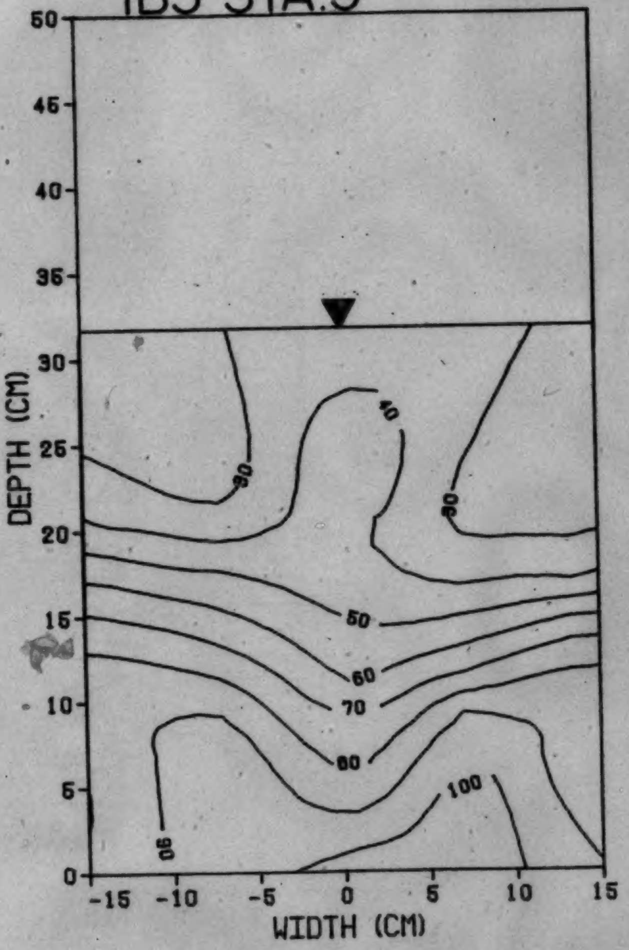


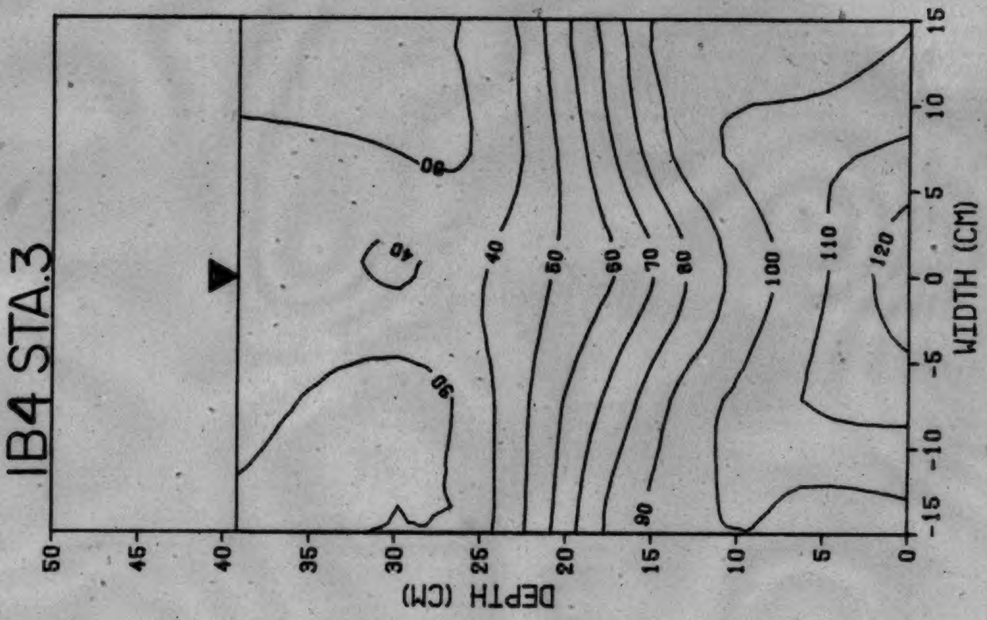
IA4 STA.3

IB2 STA.3



IB3 STA.3




IB4 STA.3
DEPTH (CM)
50
45
40
35
30
25
20
15
10
5
0
WIDTH (CM)
-15
-10
-5
0
5
10
15
90
40
40
50
60
70
80
90
100
110
120

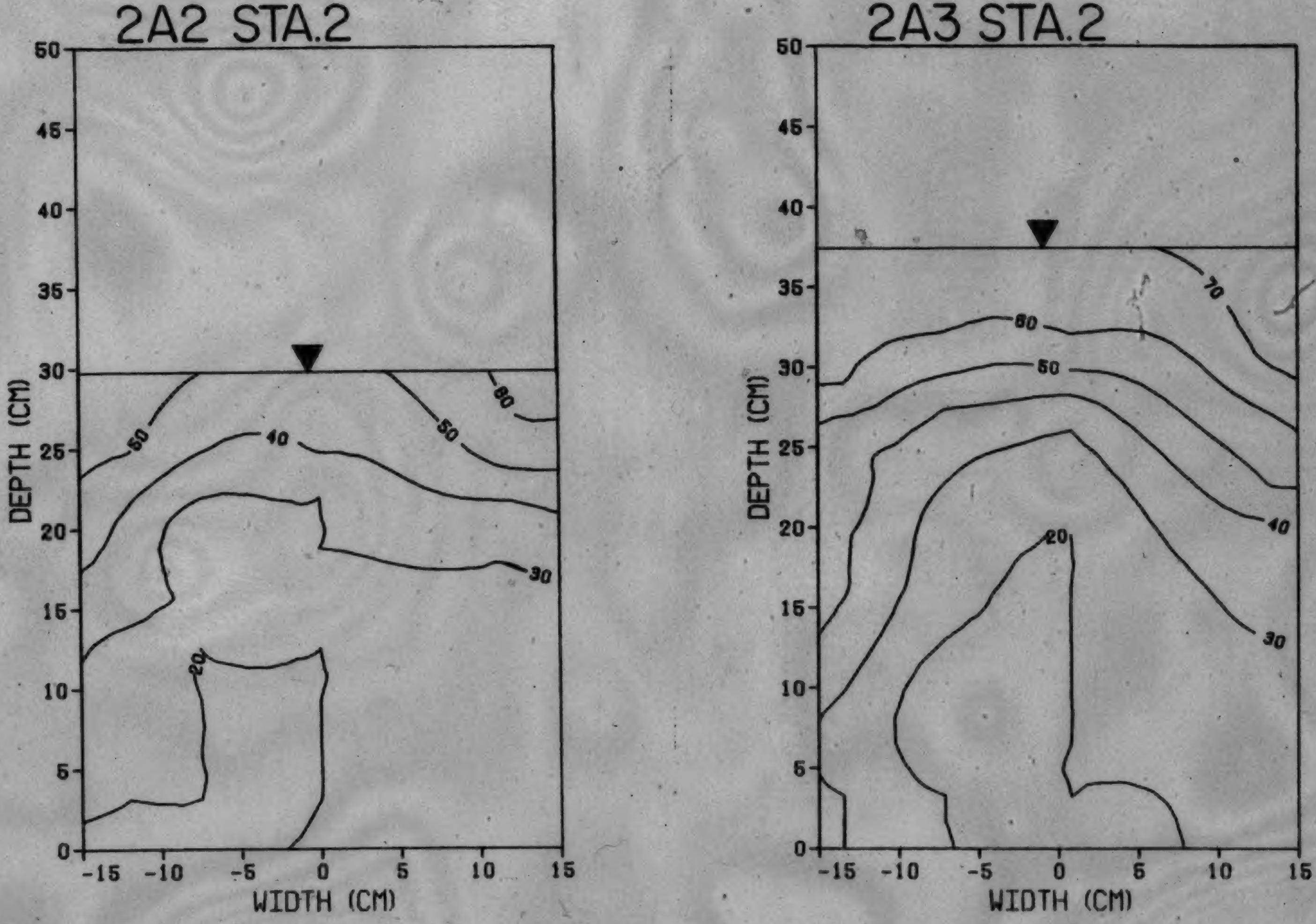
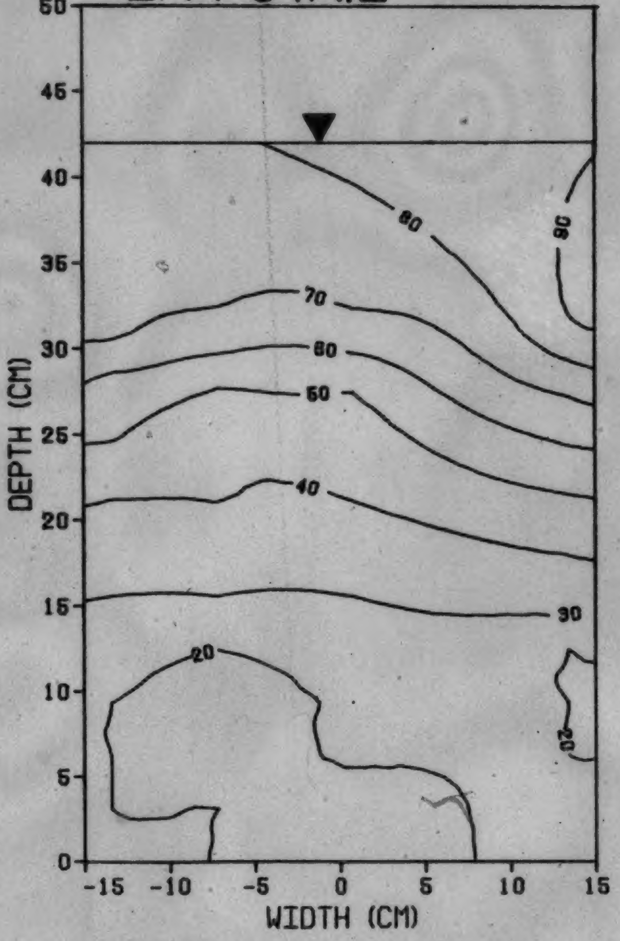
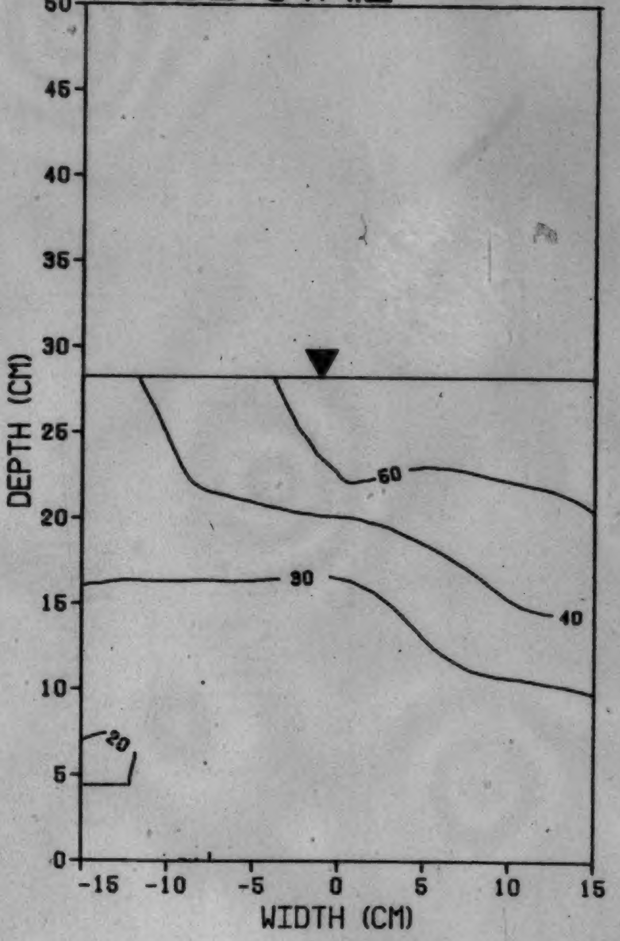


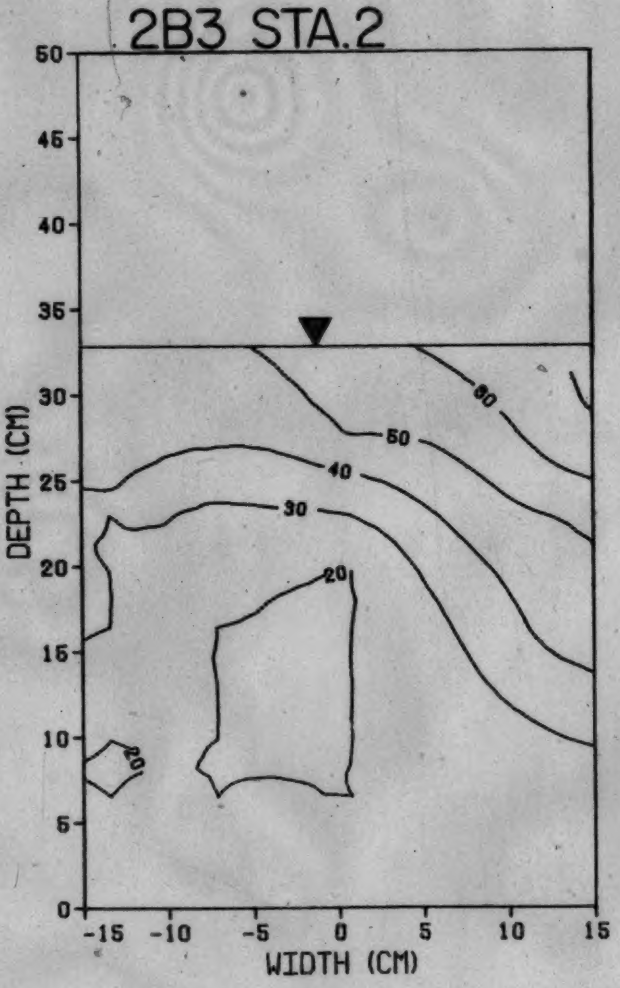
FIG. 18. Denil 2: velocity contours.

2A4 STA.2

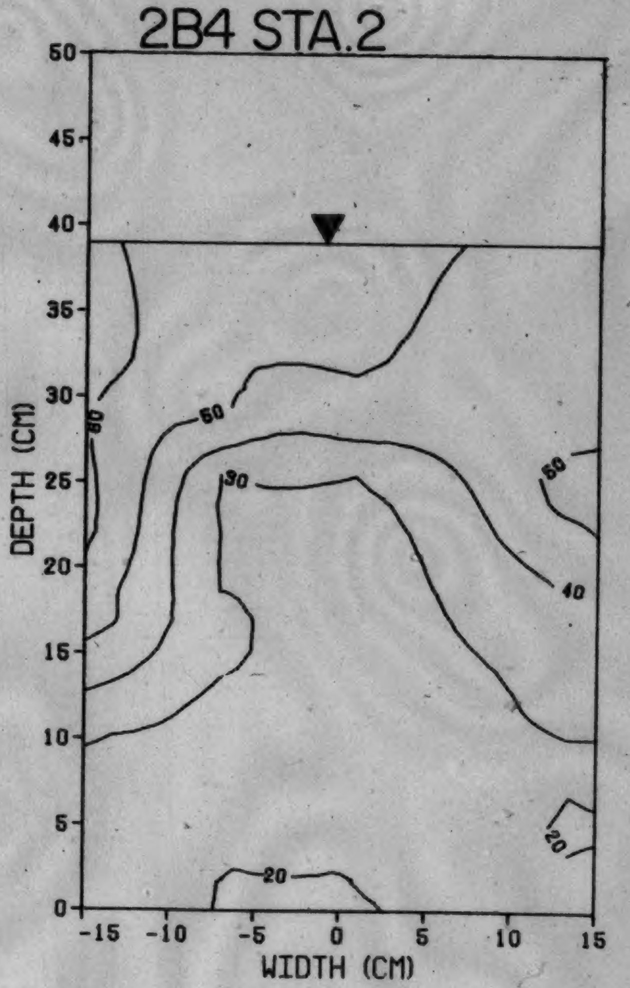


2B2 STA.2

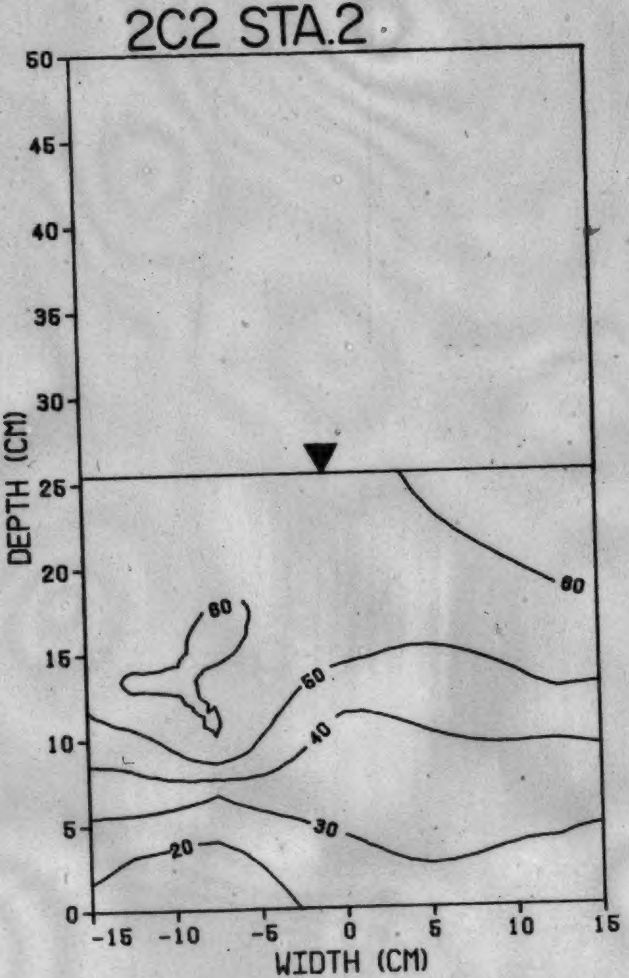


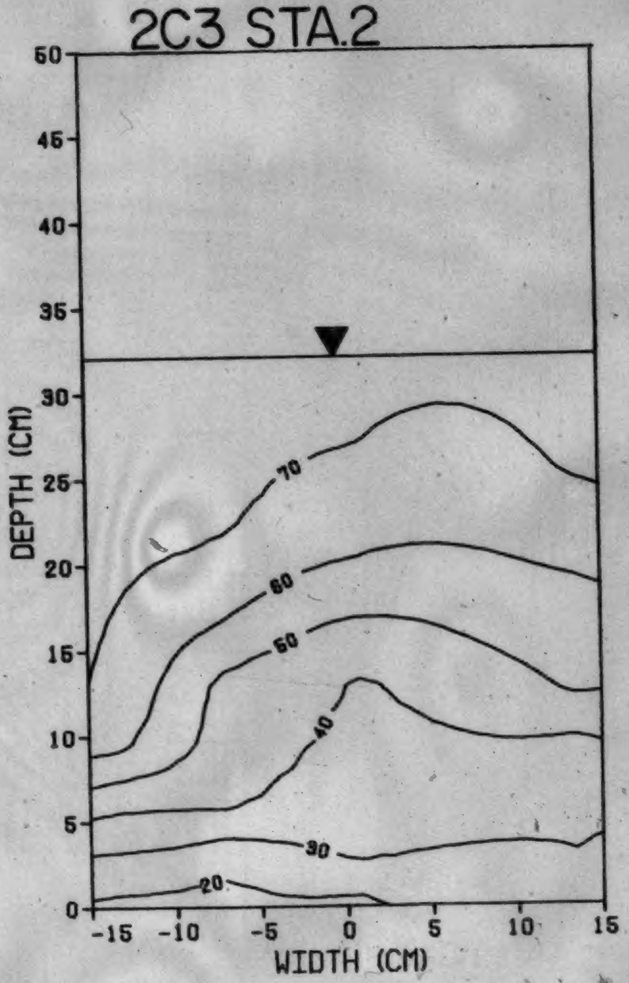


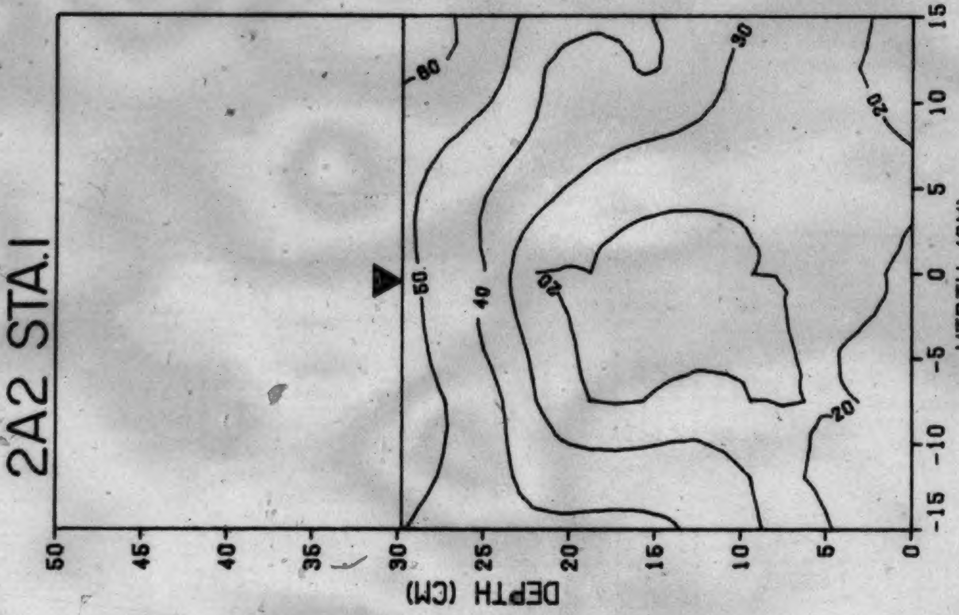
2B3 STA.2

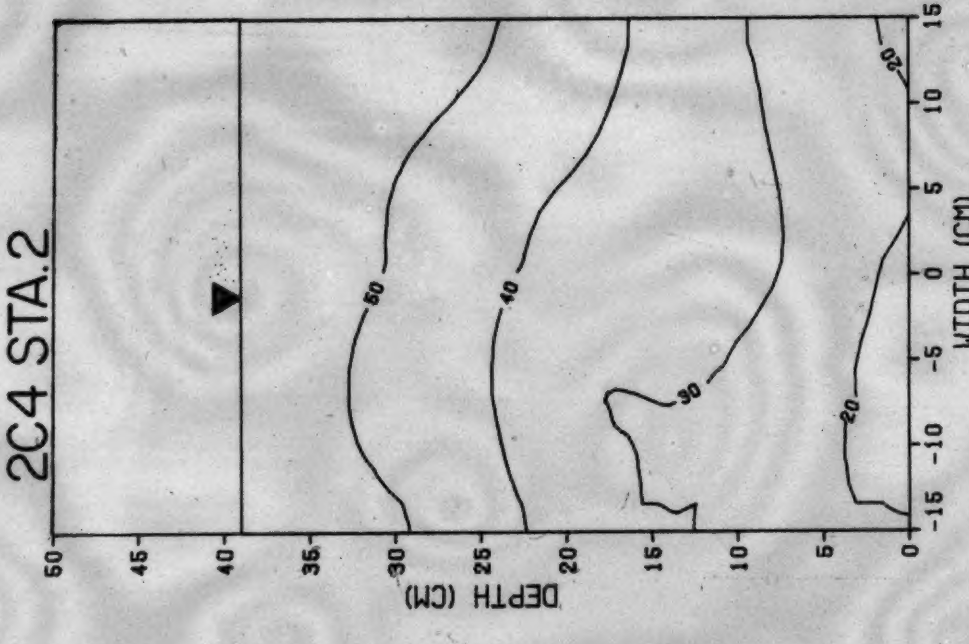


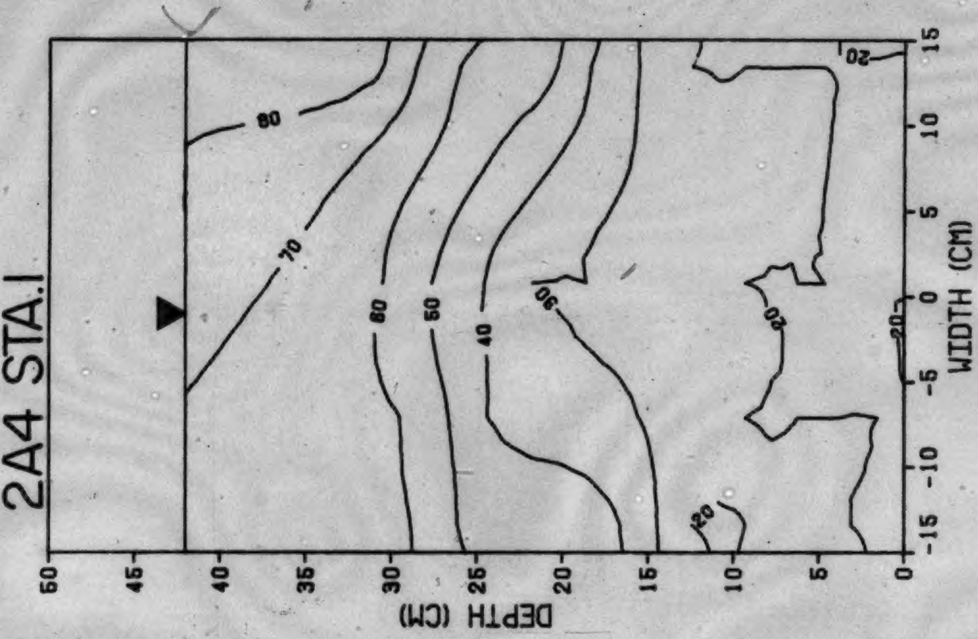
2B4 STA.2


2C2 STA.2
DEPTH (CM)
WIDTH (CM)
0
5
10
15
20
25
30
35
40
45
50
-15
-10
-5
0
5
10
15
60
60
50
40
30
20


2C3 STA.2
DEPTH (CM)
WIDTH (CM)
0
5
10
15
20
25
30
35
40
45
50
-15
-10
-5
0
5
10
15
70
60
50
40
30
20


2A2 STA.1


2C4 STA.2


2A4 STA.I
DEPTH (CM)
WIDTH (CM)
0
5
10
15
20
25
30
35
40
45
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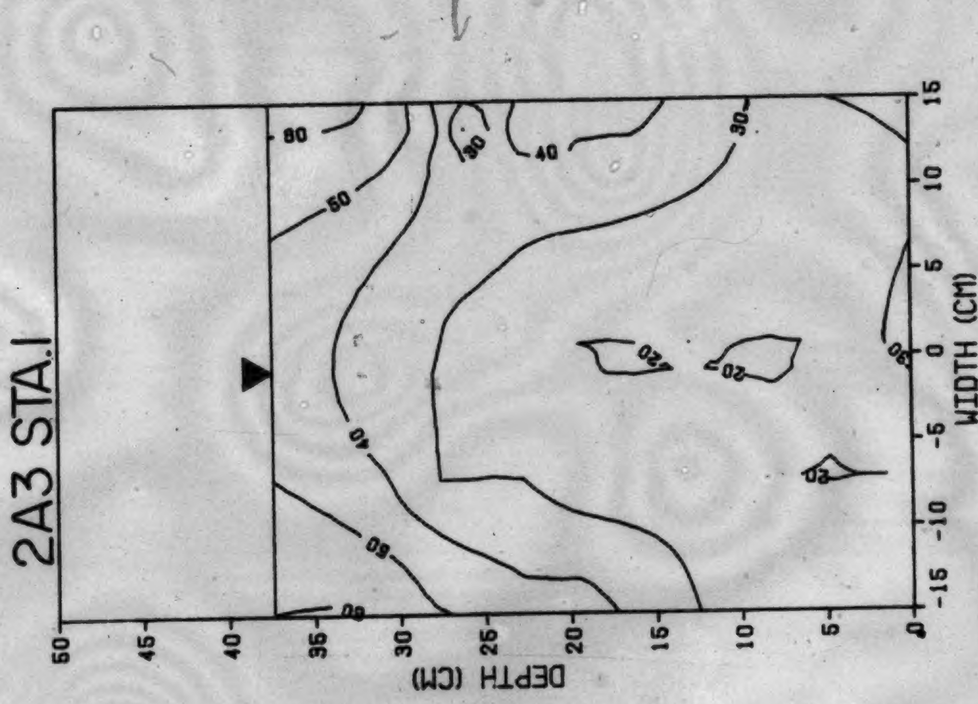
-15
-10
-5
0
5
10
15
80
70
60
50
40
30
20
20
20
20


2A3 STA.I
DEPTH (CM)
WIDTH (CM)
0
5
10
15
20
25
30
35
40
45
50
-15
-10
-5
0
5
10
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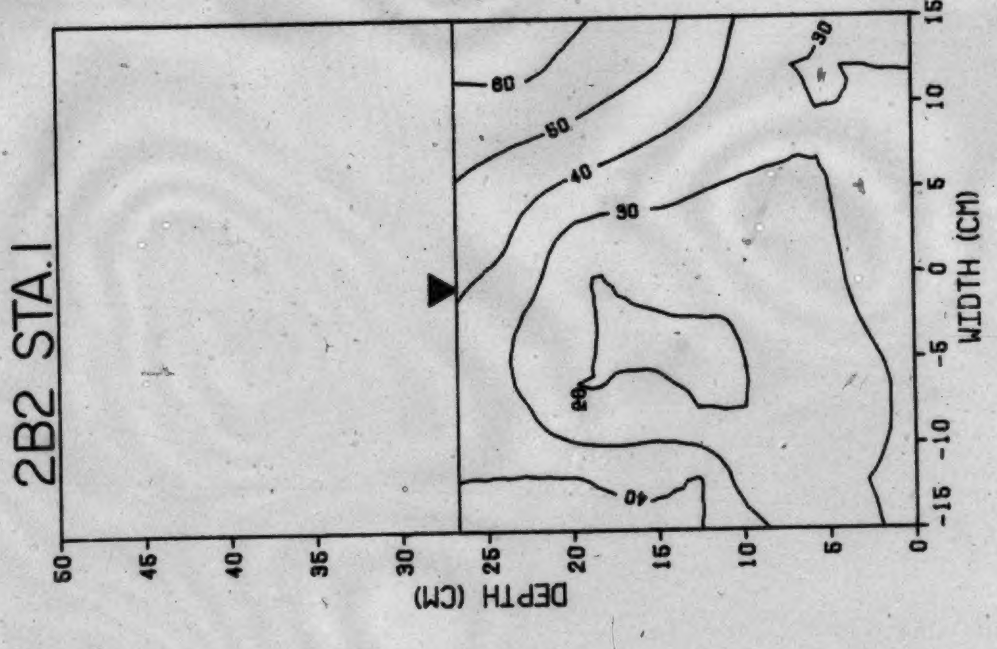
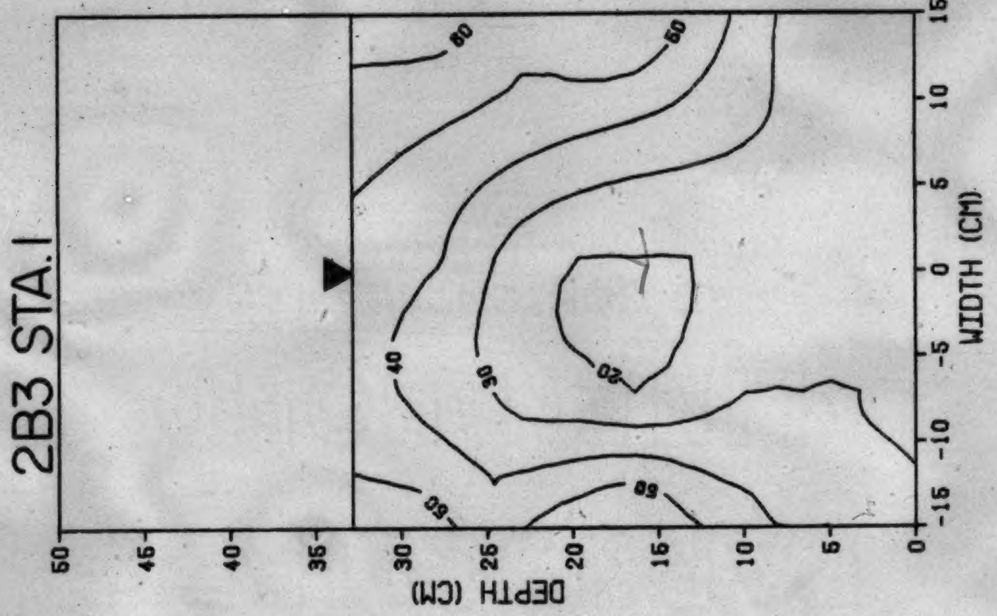
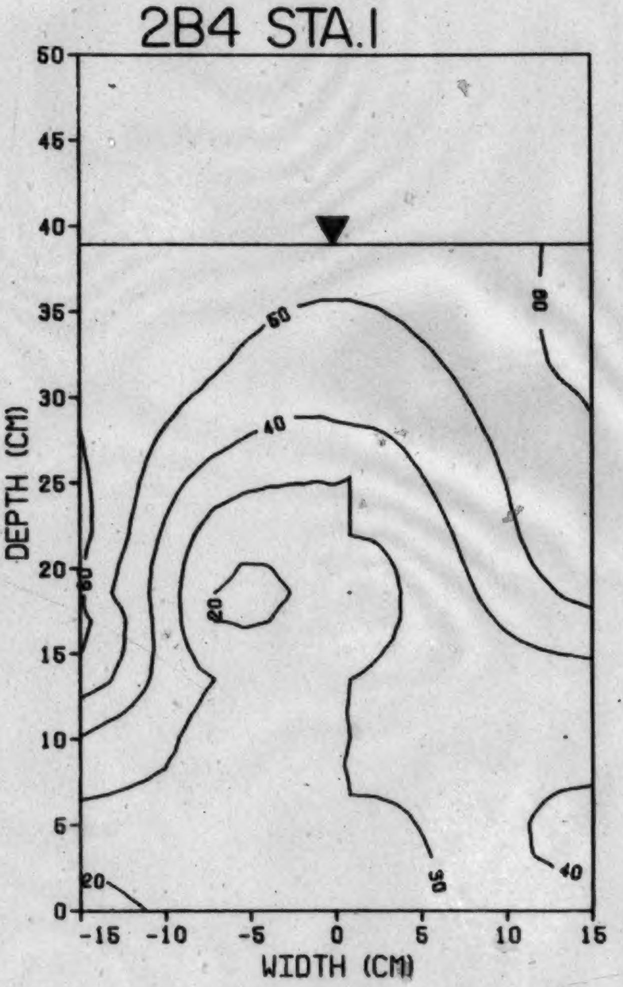
40
20
20
30
20
60
60

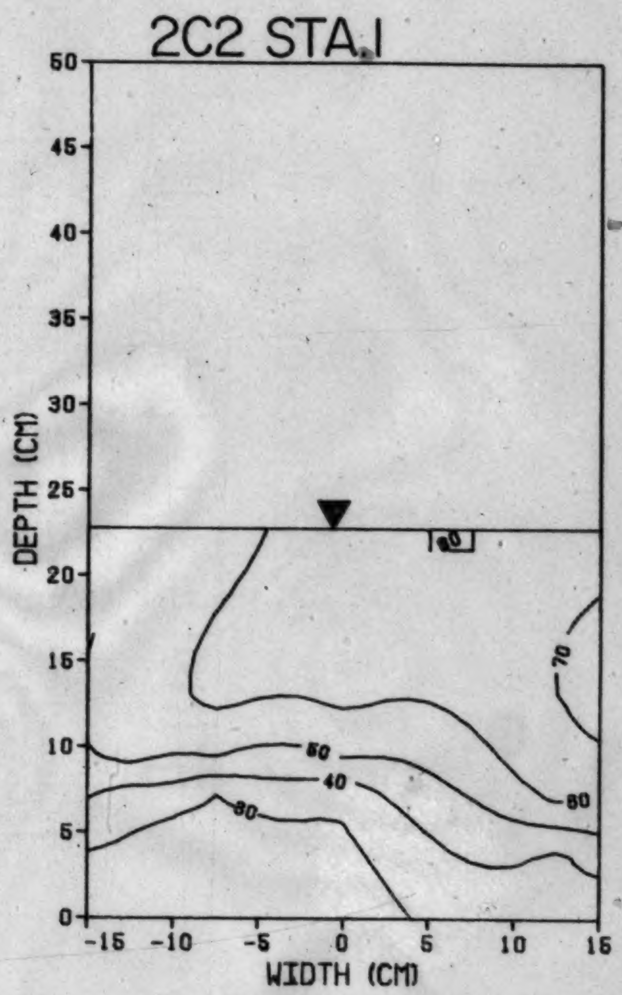


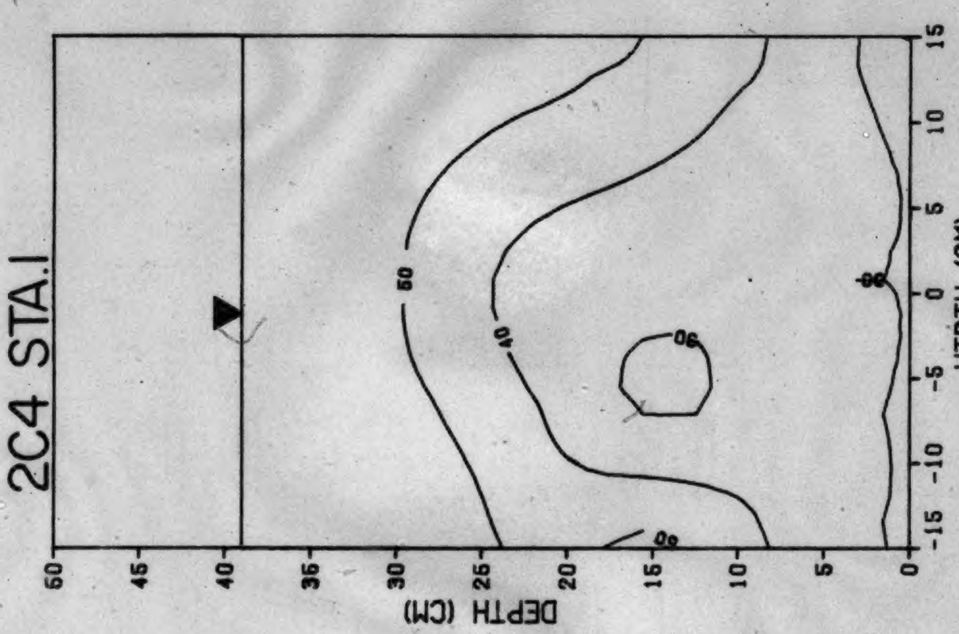
2B2 STA.1

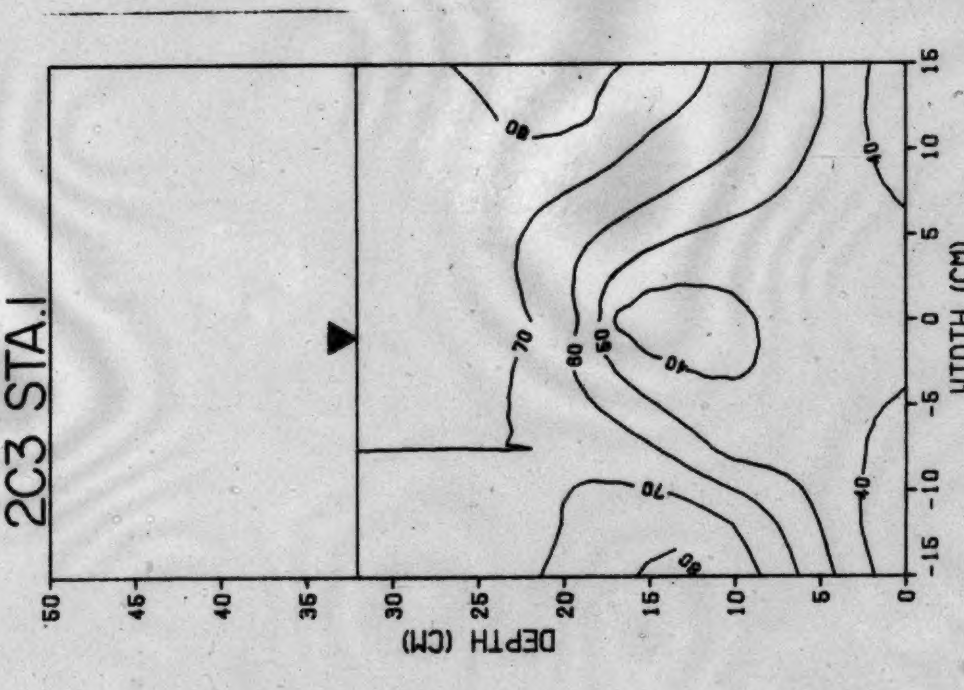


2B3 STA.1


2B4 STA.I
DEPTH (CM)
WIDTH (CM)
50
45
40
35
30
25
20
15
10
5
0
-15
-10
-5
0
5
10
15
50
40
20
30
40
60
60
20


2C2 STA.I
DEPTH (CM)
WIDTH (CM)
50
45
40
35
30
25
20
15
10
5
0
-15
-10
-5
0
5
10
15
60
70
50
40
30
60


2C4 STA.I
DEPTH (CM)
WIDTH (CM)
50
45
40
35
30
25
20
15
10
5
0
-15
-10
-5
0
5
10
15
50
40
30
30


2C3 STA.I
DEPTH (CM)
WIDTH (CM)
50
45
40
35
30
25
20
15
10
5
0
-15
-10
-5
0
5
10
15
80
70
60
50
40
70
80
40
40

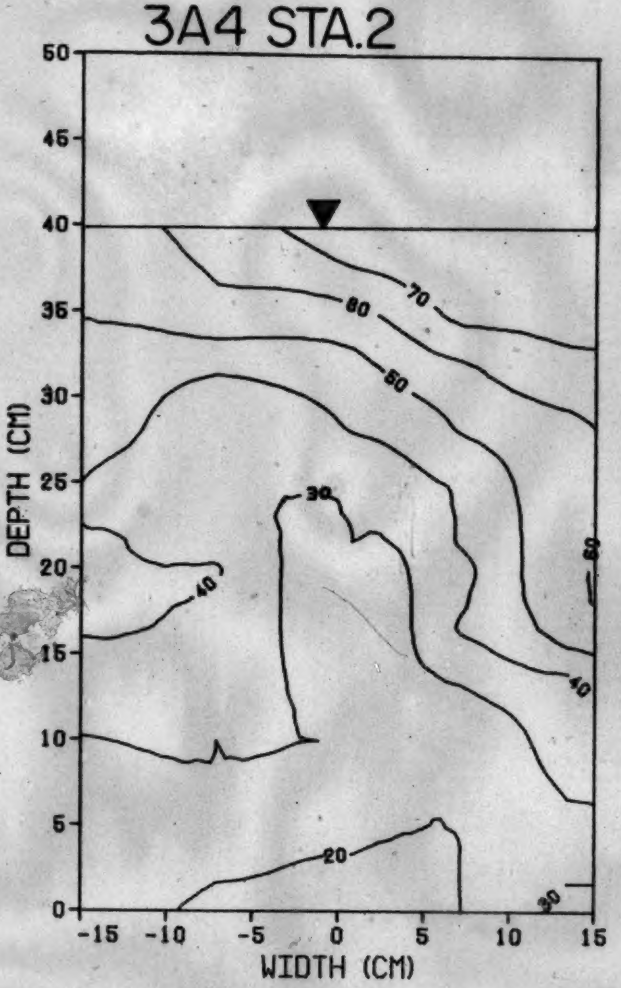


FIG. 19. Denil 3: velocity contours.

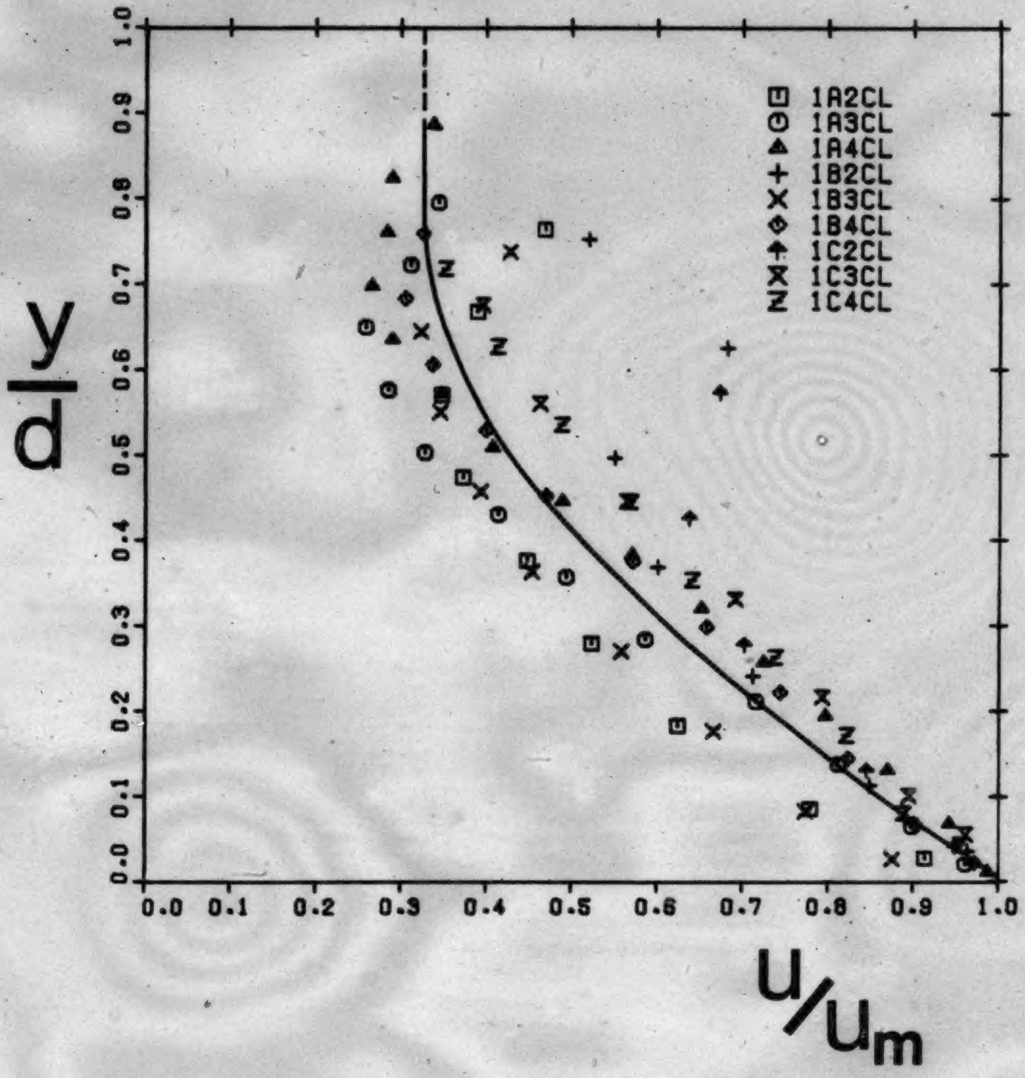


FIG. 20. Denil 1: similarity of centerline velocity profiles.

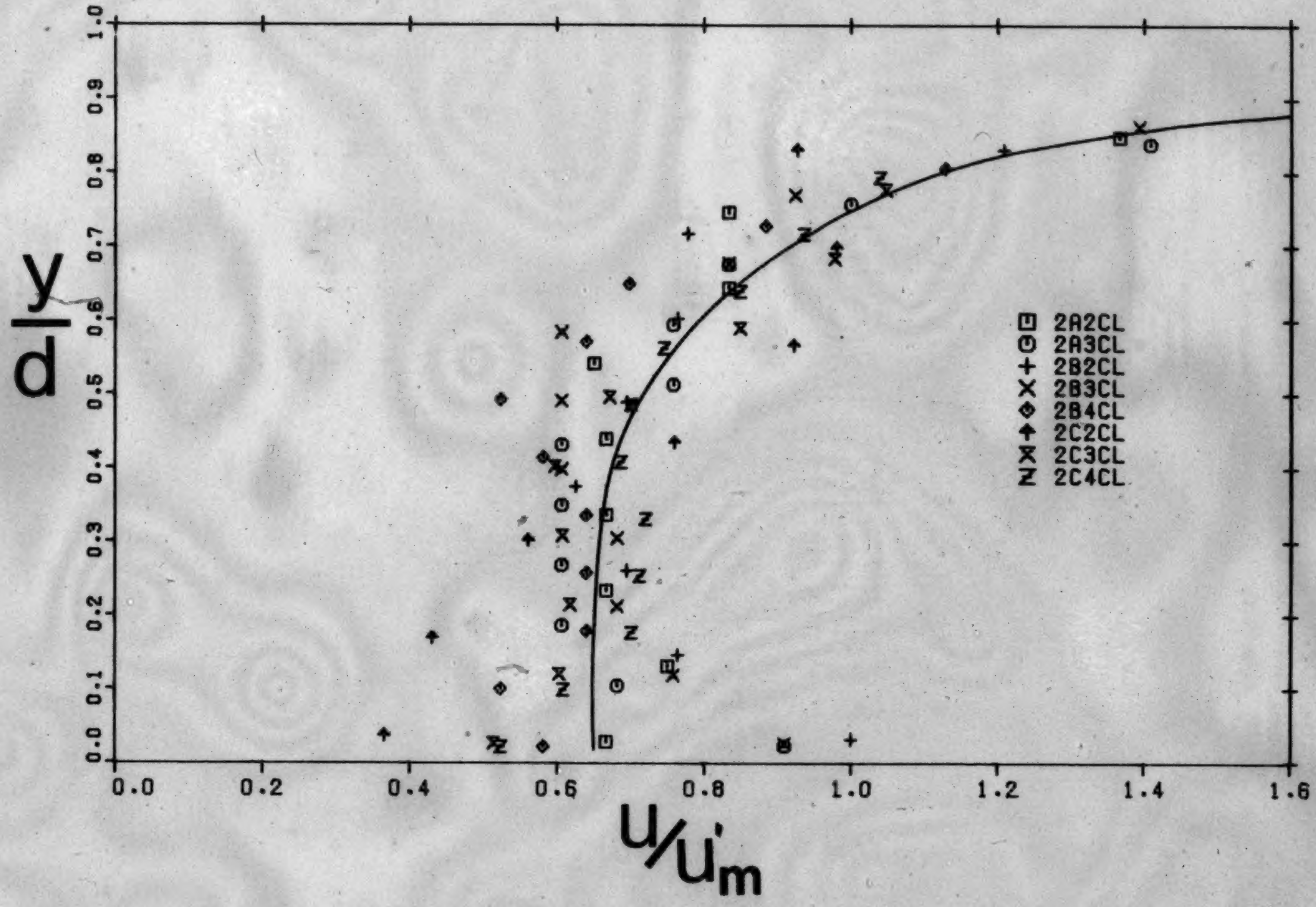


FIG. 21. Denil 2: similarity of centerline velocity profiles.

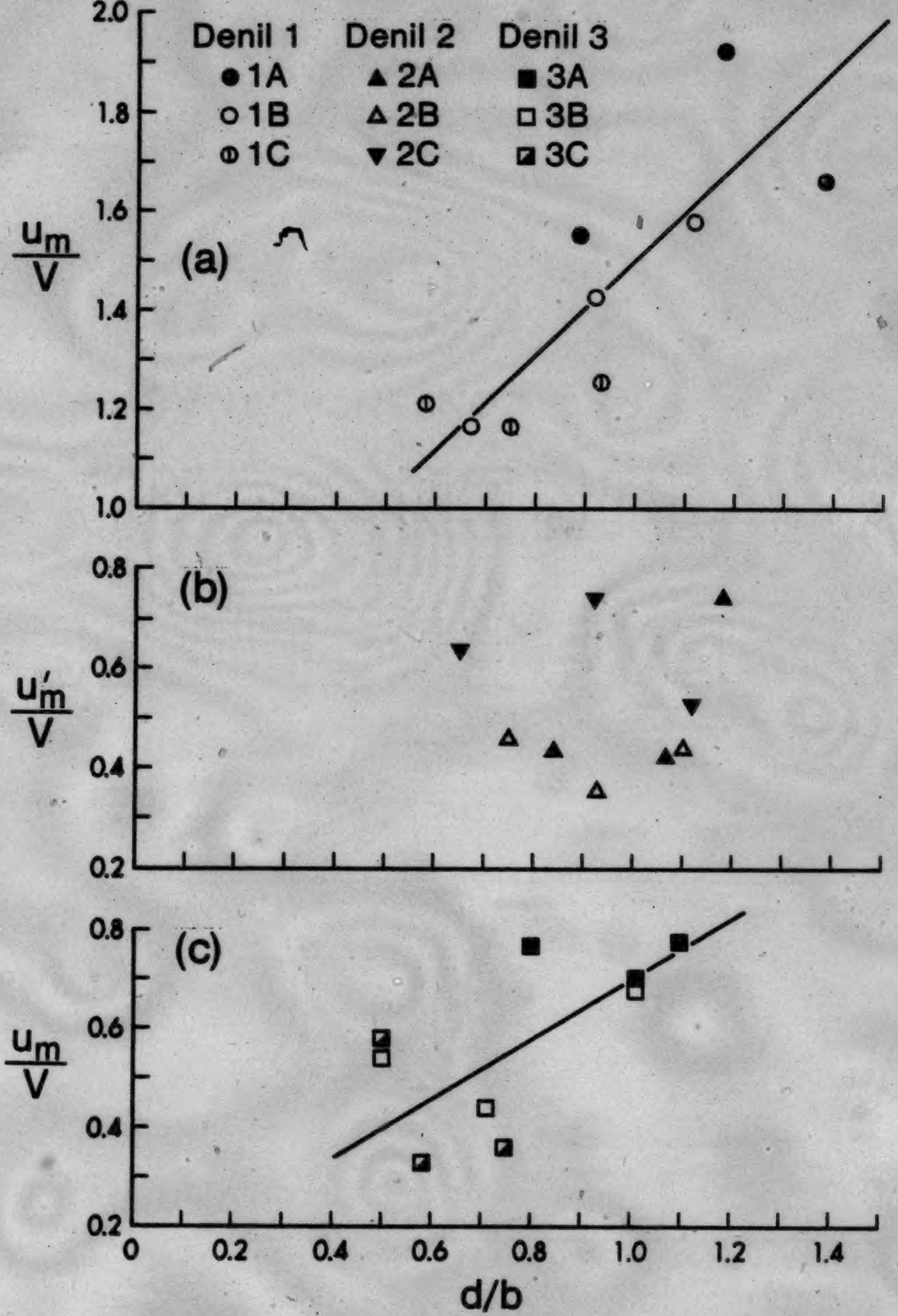


FIG. 22. Study of the velocity scale for the three fishways.

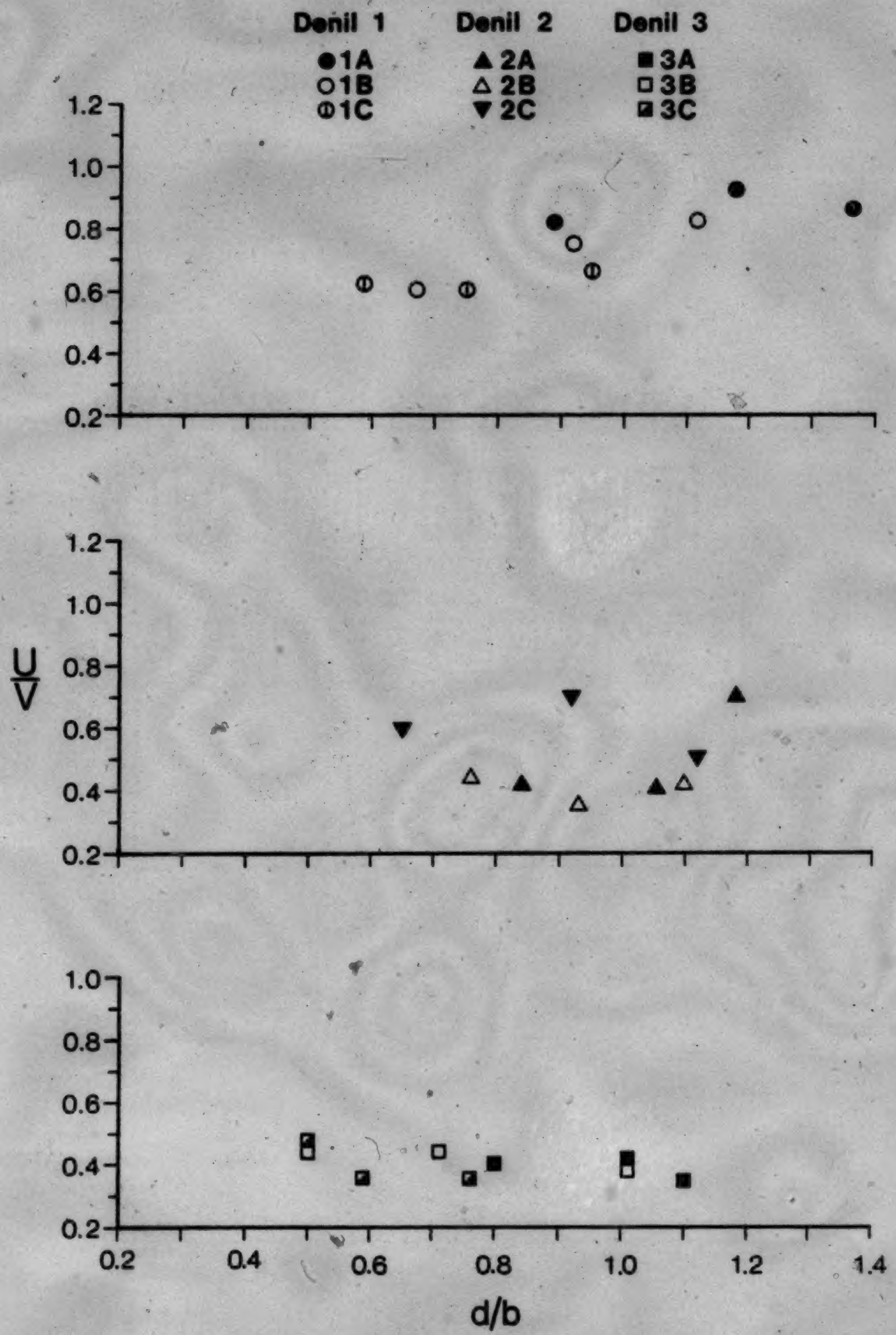


FIG. 23. Variation of the depth averaged velocity for the three fishways.

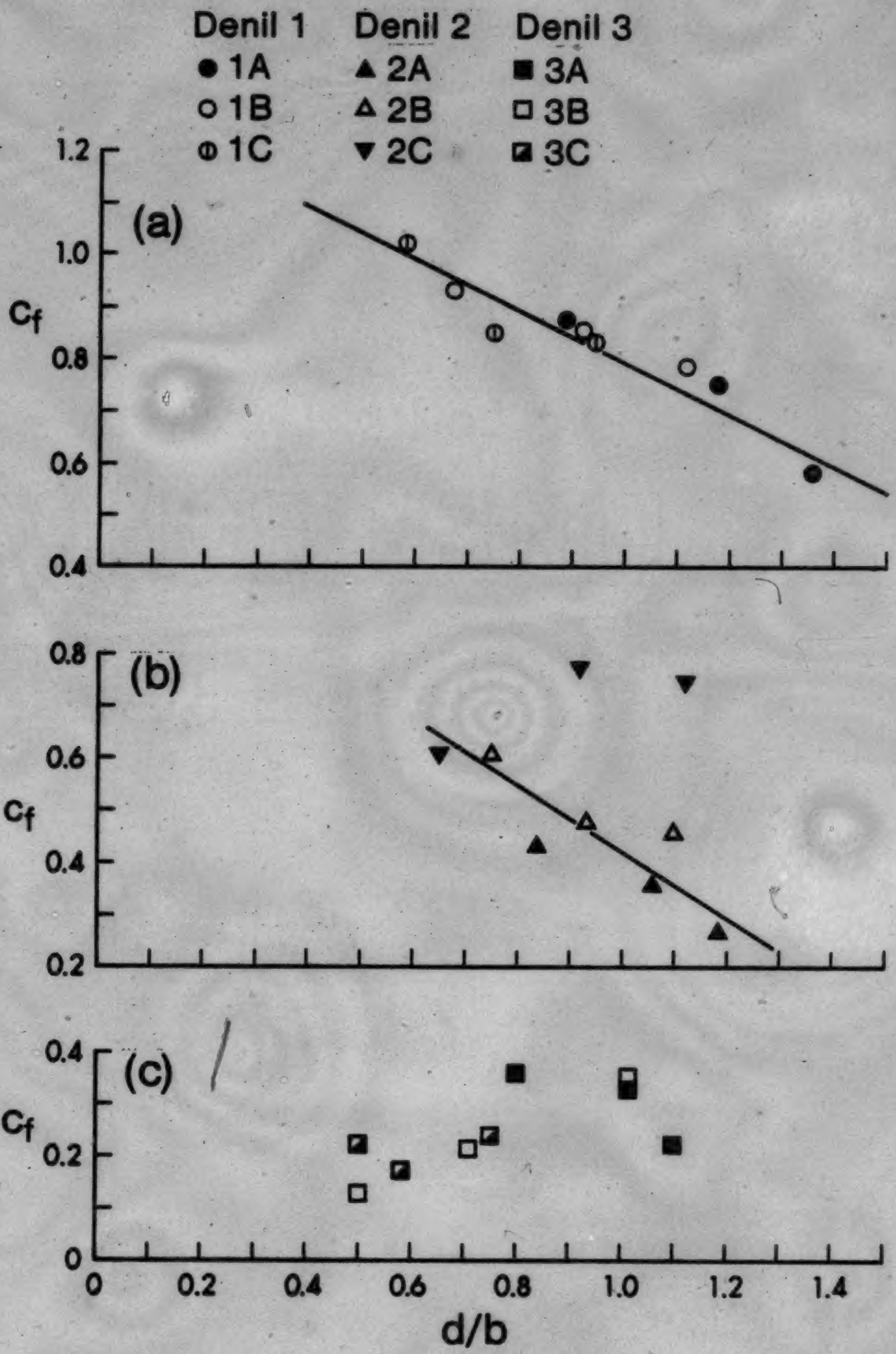


FIG. 24. Variation of the friction coefficient for the three fishways.

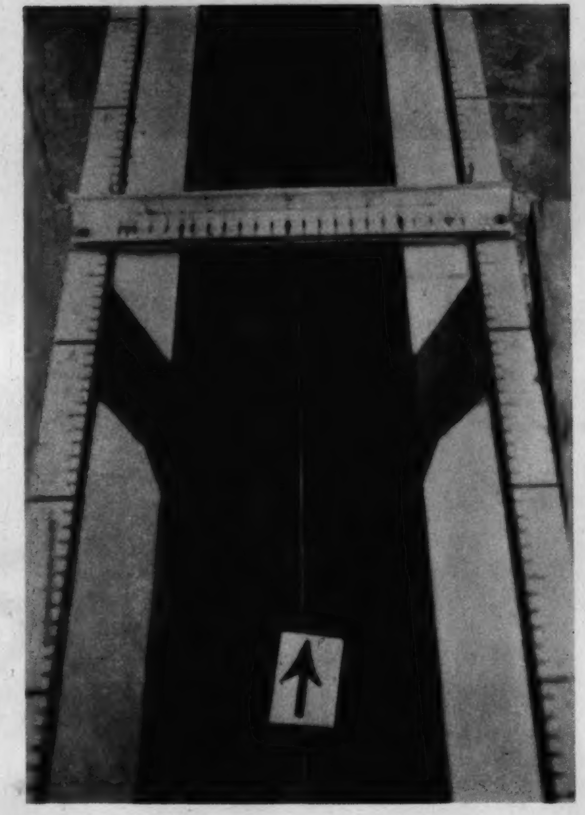


PLATE 1. Denil 1 fishway (steeppass).

PLATE 2. Denil 1 fishway (steeppass).

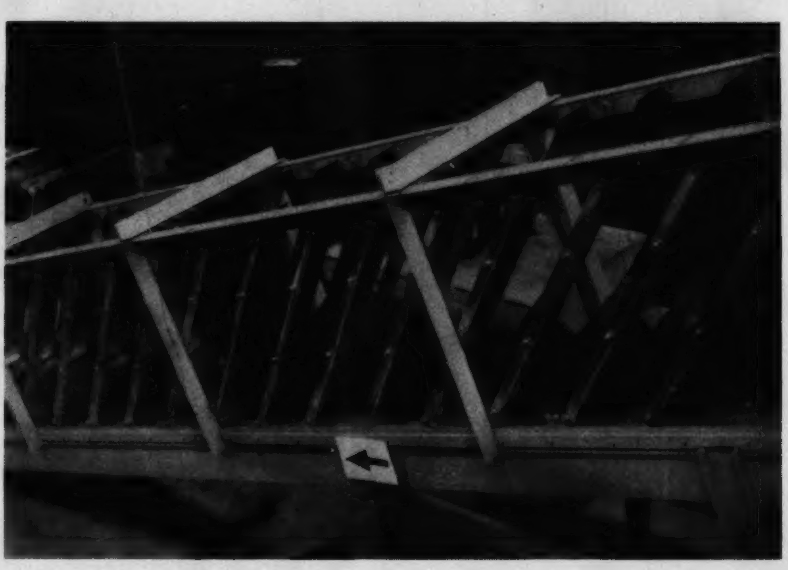


PLATE 3. Denil 2 fishway.

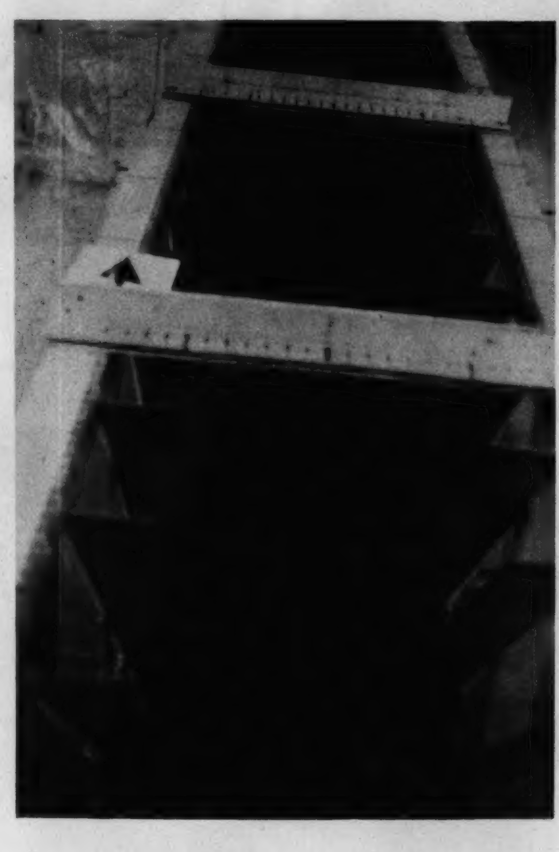


PLATE 4. Denil 2 fishway.

PLATE 5. Experimental arrangement.

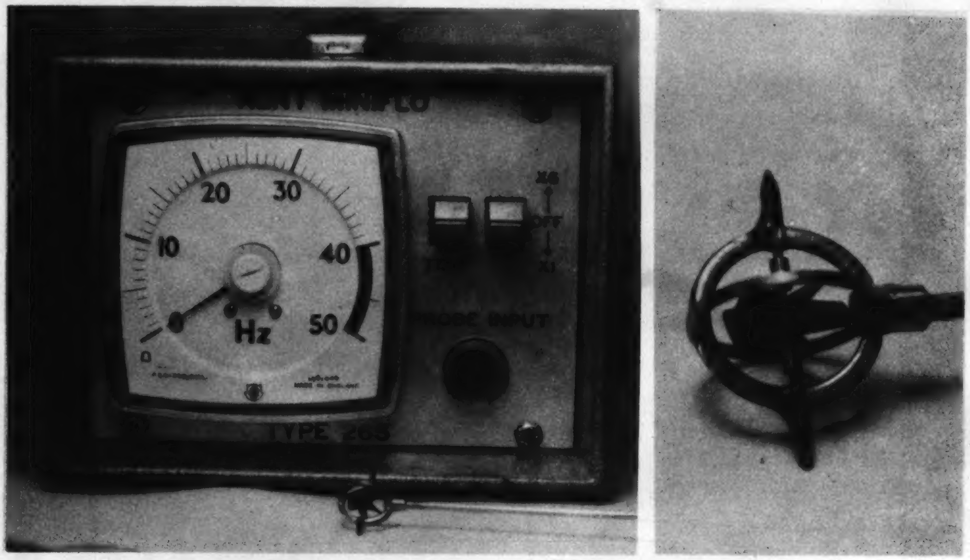


PLATE 6. Analogue indicator and sensing probe.

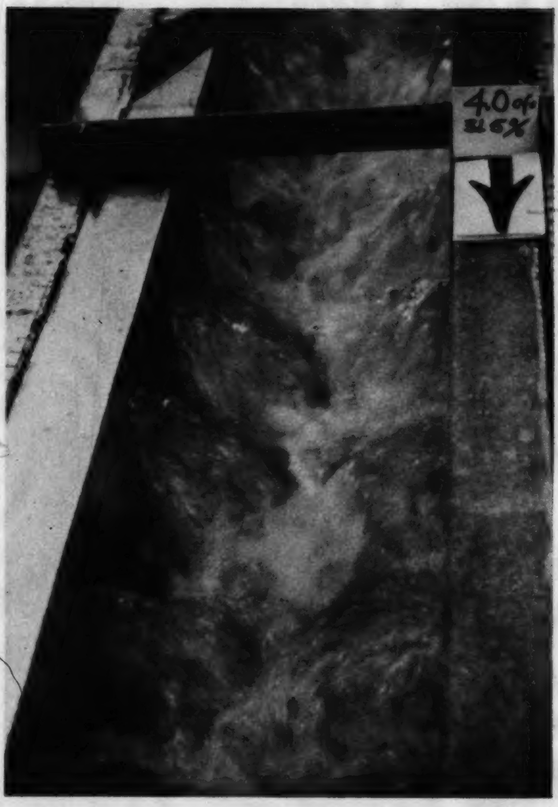


PLATE 7. Denil 1 displaying very strong lateral streams at a slope of 31.5% (discharge 113.3 L/s, experiment 1C4).

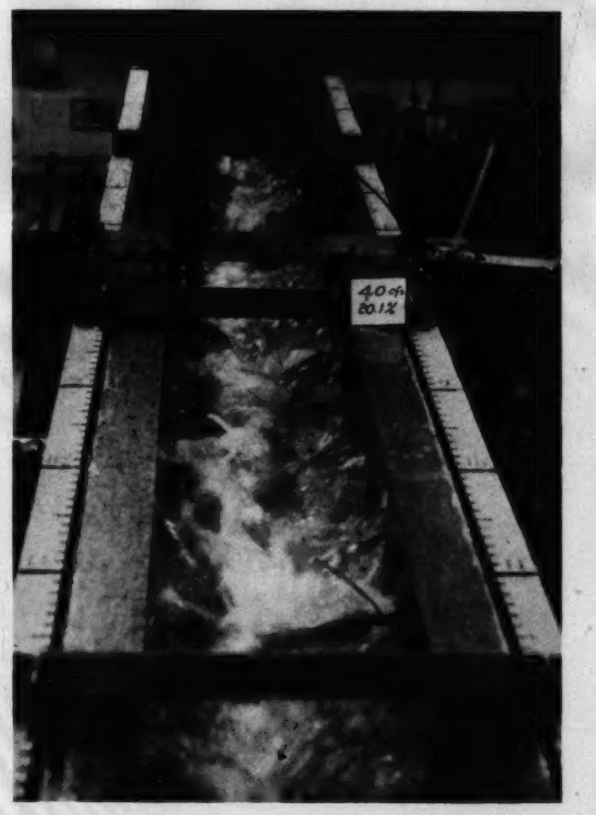


PLATE 8. Denil 1 displaying strong lateral streams at a slope of 20.1% (looking upstream, experiment 1B4).

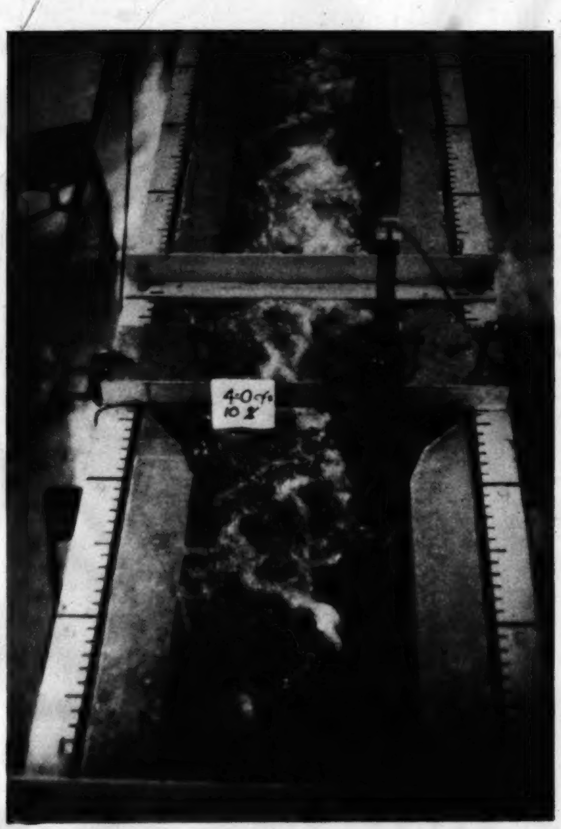


PLATE 9. Denil 1 displaying weak lateral streams at a slope of 10.0% (looking upstream, experiment 1A4).

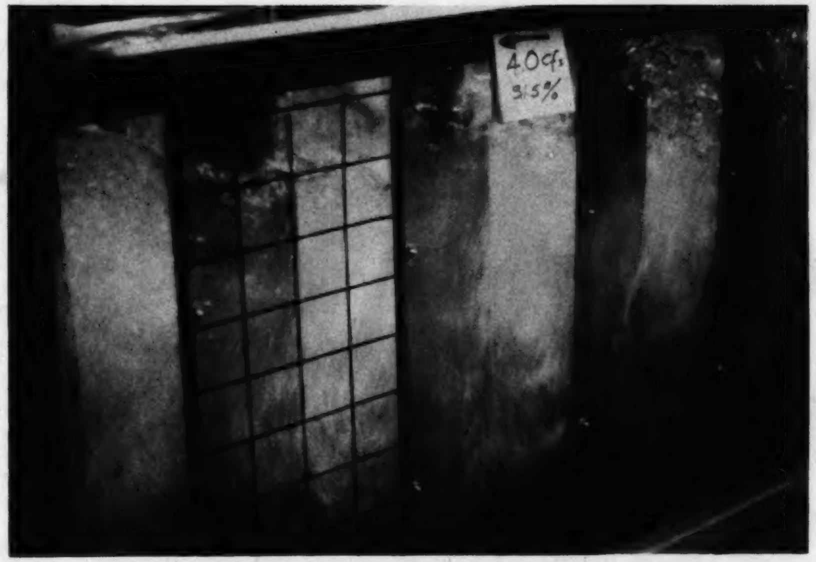


PLATE 10. Denil 1 displaying very strong and large scale circulation patterns at a slope of 31.5% (discharge 113.3 L/s, experiment 1C4).

PLATE 11. Denil 1 displaying weak but large scale circulation patterns at a slope of 10.0% (discharge 113.3 L/s, experiment 1A4).

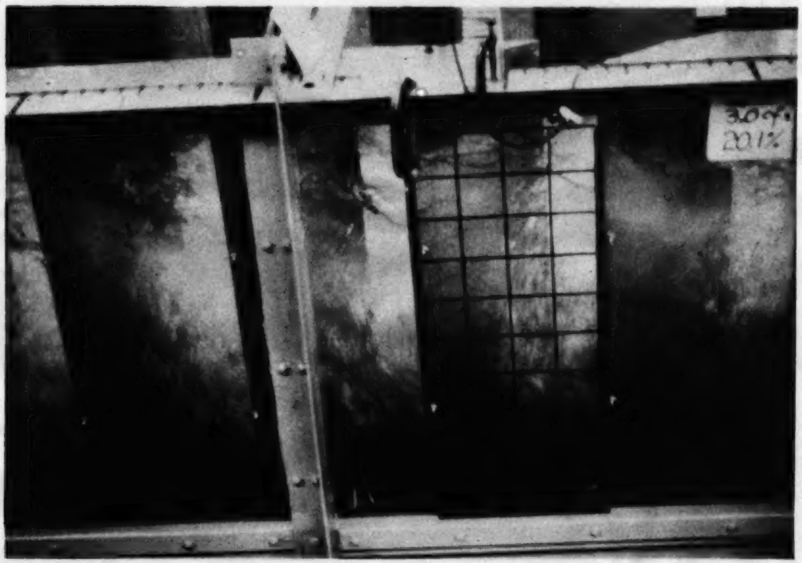


PLATE 12. Denil 1 displaying strong and large circulation patterns at a slope of 20.1% (discharge 85.0 L/s, experiment 1B3).

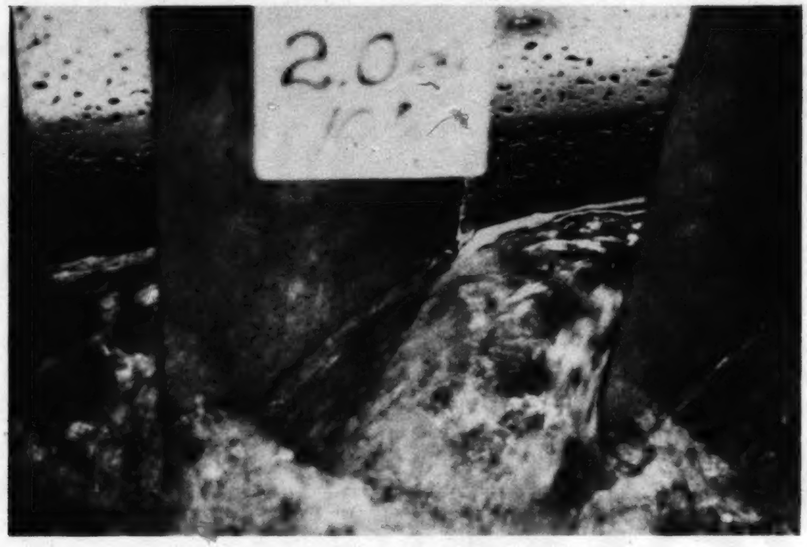


PLATE 13. Denil 1 displaying weak lateral streams at a slope of 10.0% and a discharge of 56.6 L/s (experiment 1A2).

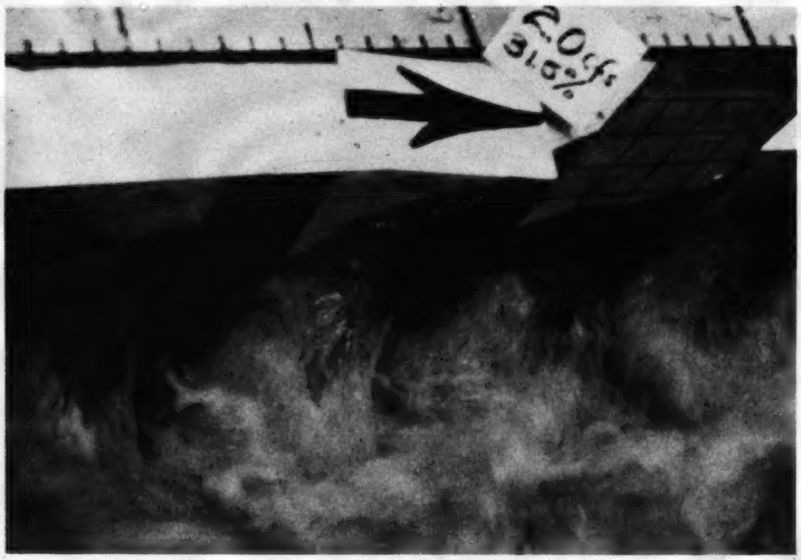


PLATE 14. Denil 1 displaying strong lateral streams at a slope of 31.5% and a discharge of 56.6 L/s (experiment 1C2).

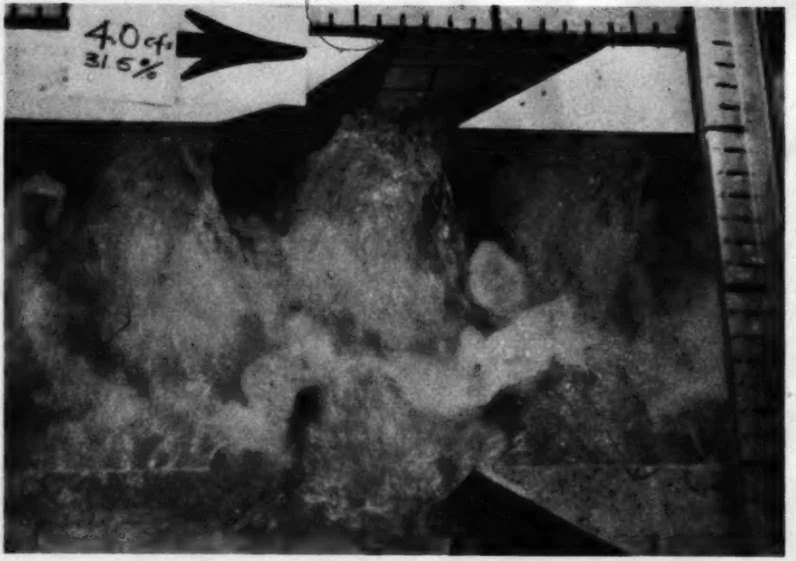


PLATE 15. Denil 1 displaying very strong lateral streams at a slope of 31.5% and a discharge of 113.3 L/s (experiment 1C4).

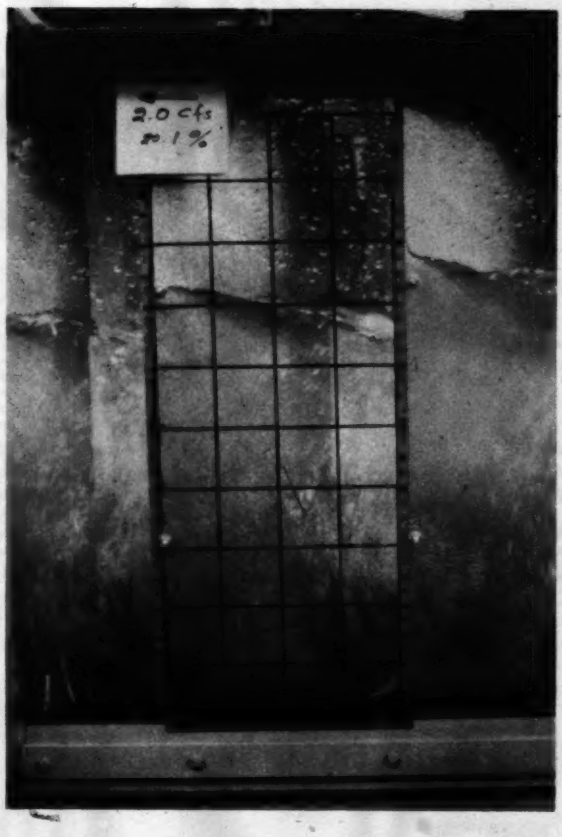


PLATE 16. Denil 1 displaying sizable water level differences from one vane to the next (discharge 56.6 L/s, experiment 1B2).

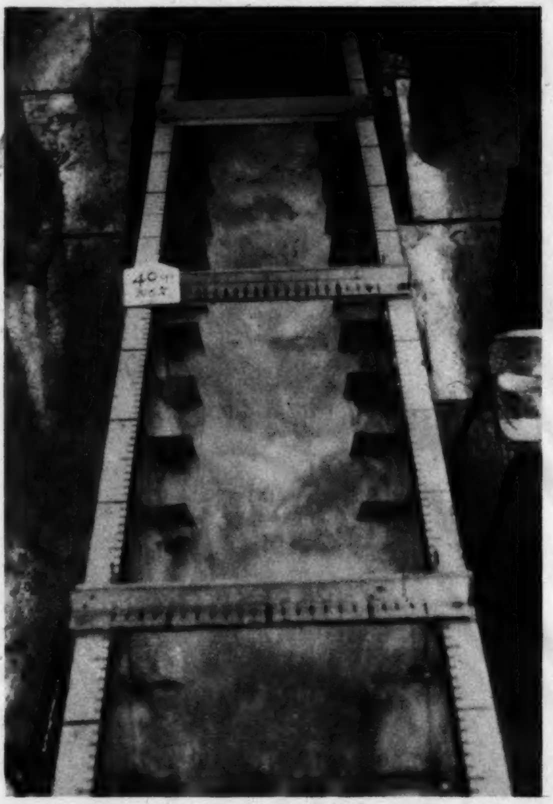


PLATE 17. Denil 2 displaying fast moving water surface and lateral streams confined between wall vanes (discharge 113.3 L/s, experiment 2C4).

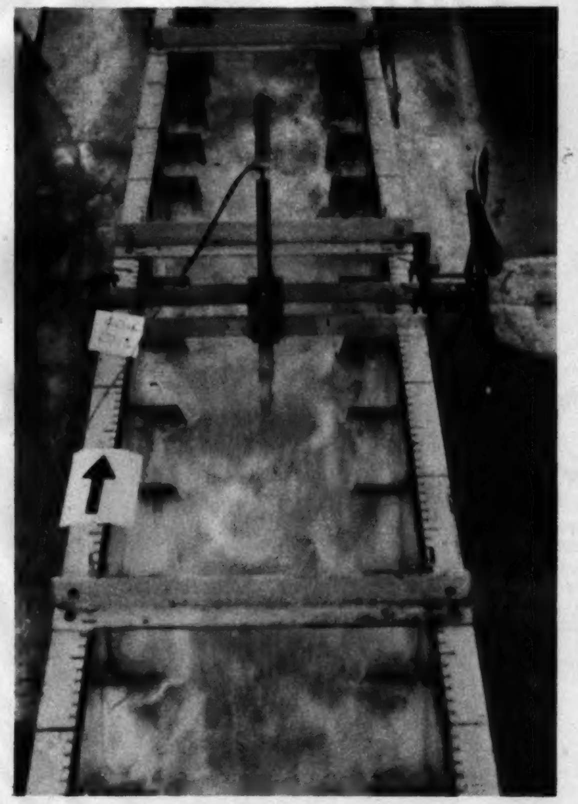


PLATE 18. Denil 2 displaying fast moving water surface and lateral streams confined between wall vanes (experiment 2B4).

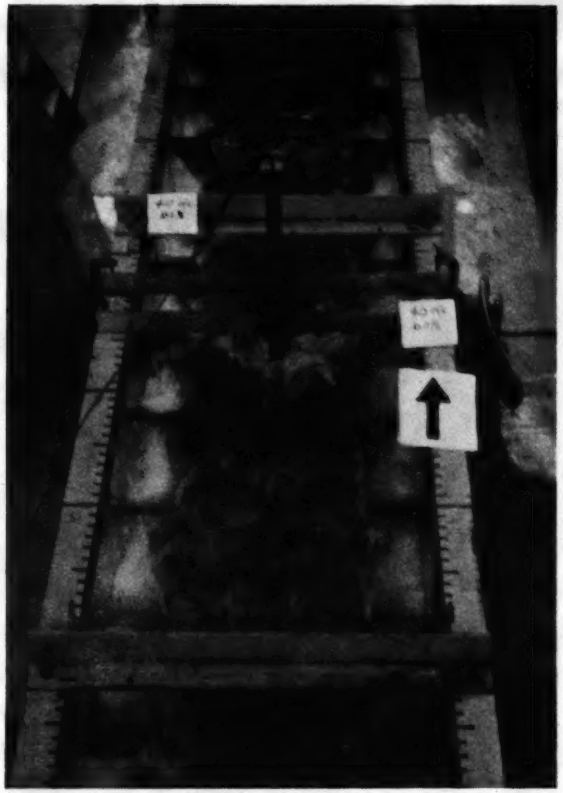


PLATE 19. Denil 2 displaying fast moving water surface and lateral streams confined between wall vanes (experiment 2A4).

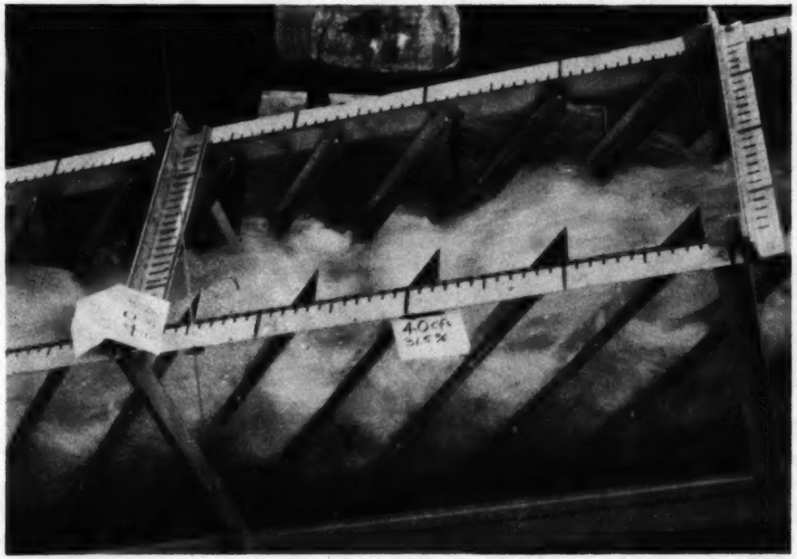


PLATE 20. Denil 2 displaying water surface wave patterns and spiral motions of the lateral streams (experiment 2C4).

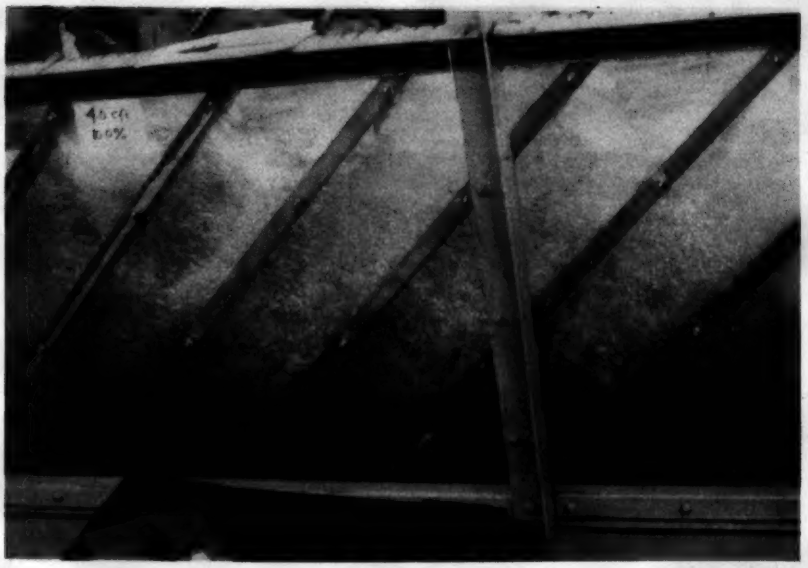


PLATE 21. Denil 2 displaying low air entrainment and velocities, as well as an inward motion near the flume bottom (experiment 2A4).

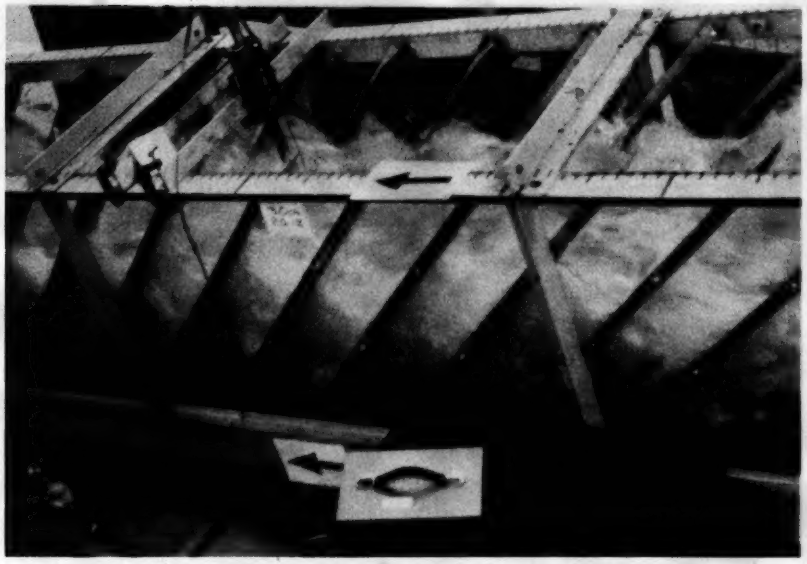


PLATE 22. Denil 2 displaying water surface wave patterns and spiral motions of the lateral streams (experiment 2B3).

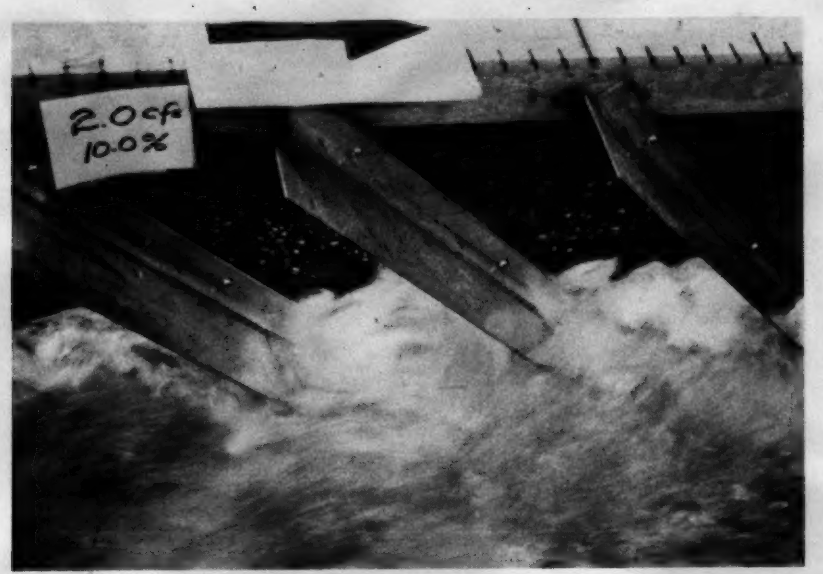


PLATE 23. Denil 2 showing the effect of lateral streams at a slope of 10.0% and a discharge of 56.6 L/s (experiment 2A2).

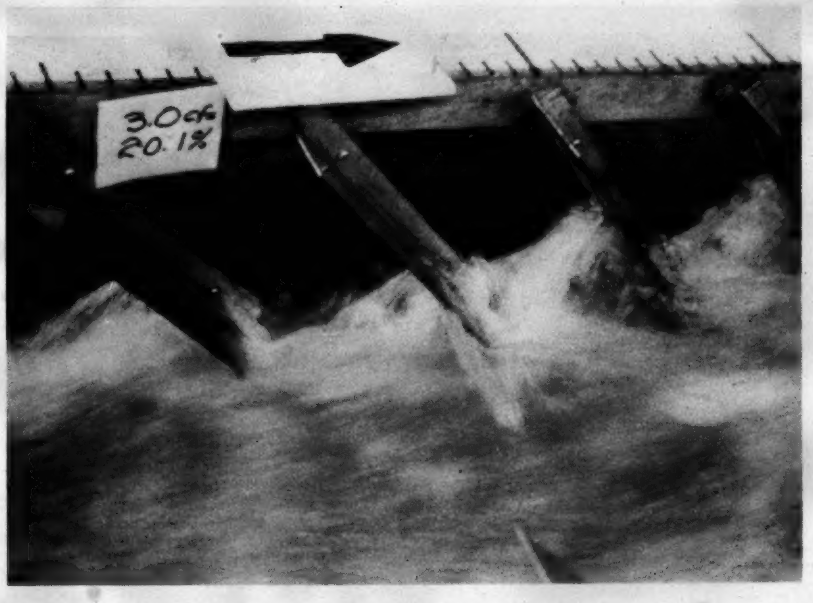


PLATE 24. Denil 2 displaying strong lateral streams at a slope of 20.1% and a discharge of 85.0 L/s (experiment 2B3).

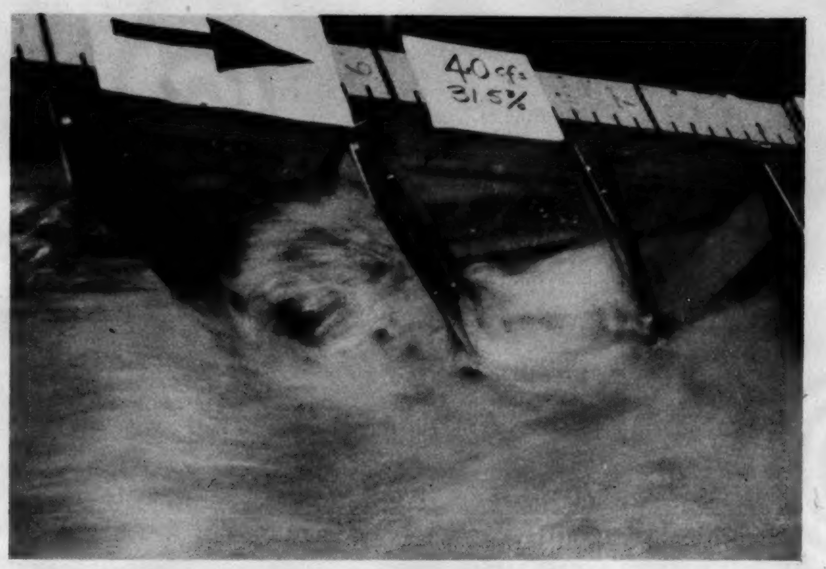


PLATE 25. Denil 2 displaying very strong lateral streams at a slope of 31.5% and a discharge of 113.3 L/s (experiment 2C4).

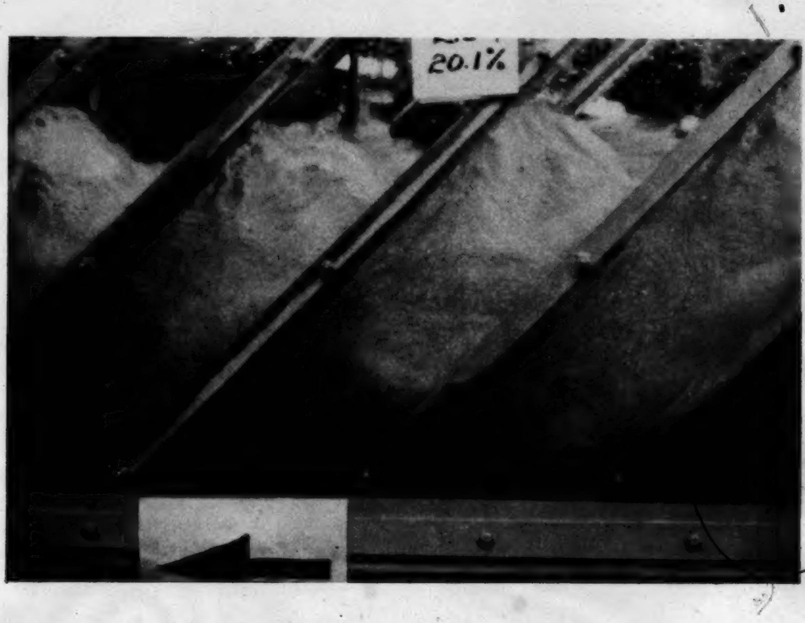


PLATE 26. Denil 2 displaying spiral motions of the lateral streams near the water surface and inward motion near the flume bottom (discharge 56.6 L/s, experiment 2B2).

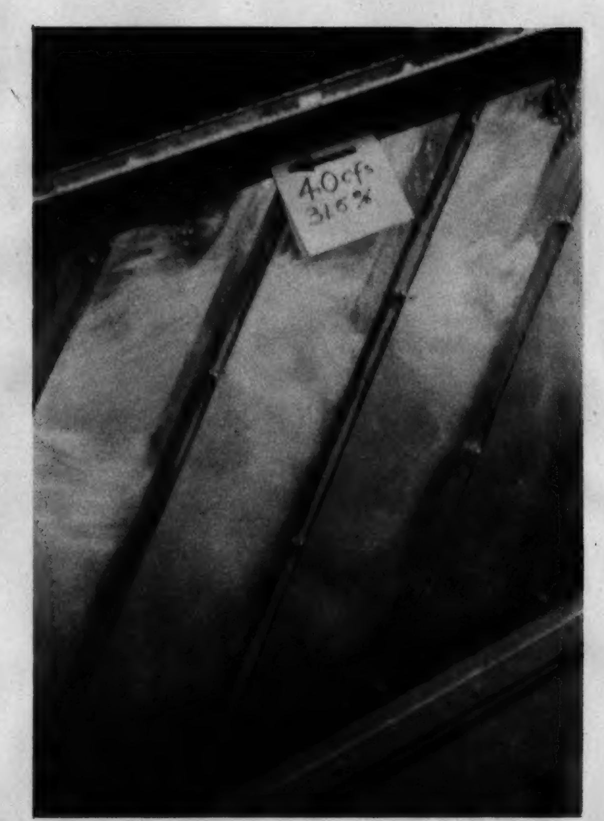


PLATE 27. Denil 2 displaying spiral motions of the lateral streams near the water surface and inward motion near the flume bottom (discharge 113.3 L/s, experiment 2C4).

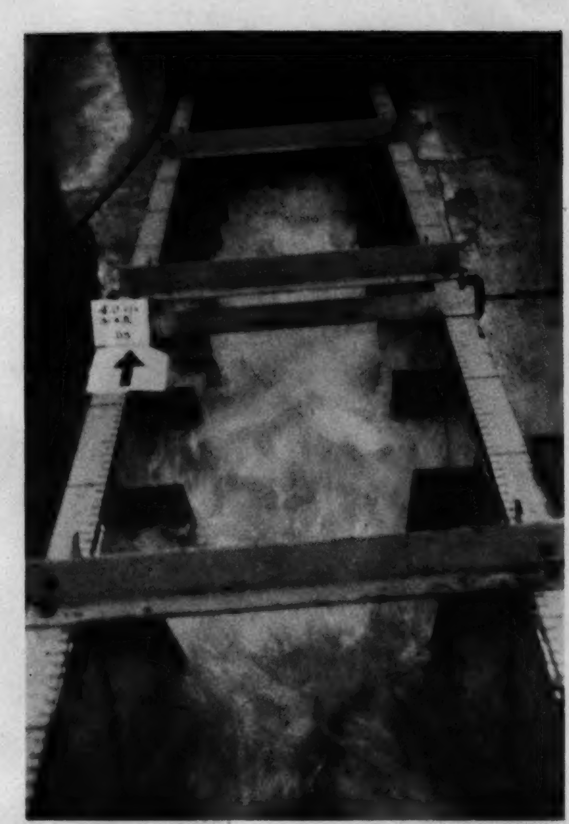


PLATE 28. Denil 3 displaying fast moving water surface and lateral streams confined between wall vanes (discharge 113.3 L/s, experiment 3C4).

PLATE 29. Denil 3 displaying fast moving water surface and lateral streams confined between wall vanes (experiment 3B4).

PLATE 30. Denil 3 displaying fast moving water surface and lateral streams confined between wall vanes (experiment 3A4).

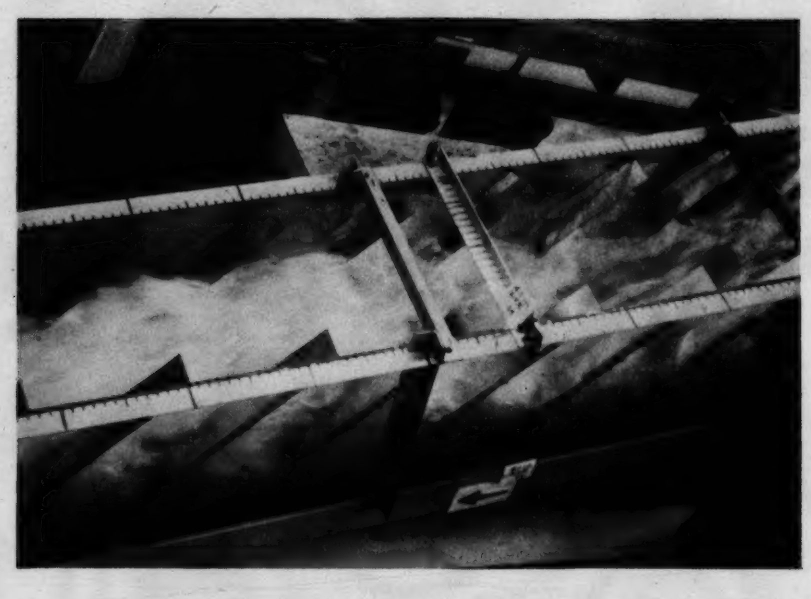


PLATE 31. Denil 3 displaying water surface wave patterns and spiral motions of the lateral streams (slope 31.5%, discharge 113.3 L/s, experiment 3C4).

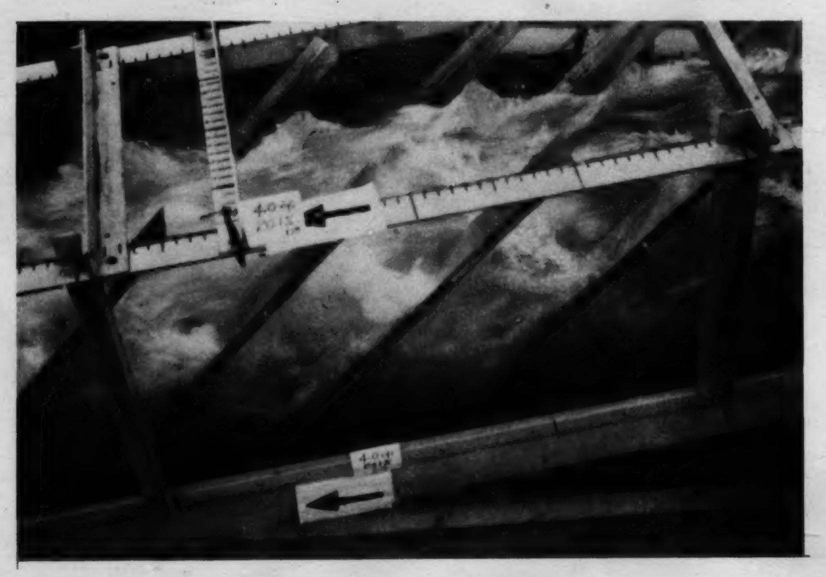


PLATE 32. Denil 3 displaying water surface wave patterns and spiral motions of the lateral streams (discharge 113.3 L/s, experiment 3B4).

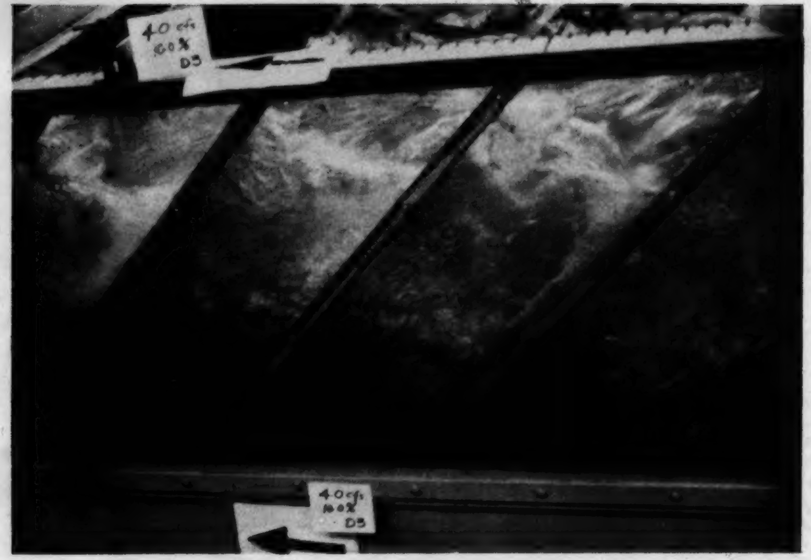


PLATE 33. Denil 3 displaying low air entrainment and velocities, as well as an inward motion near the flume bottom (experiment 3A4).

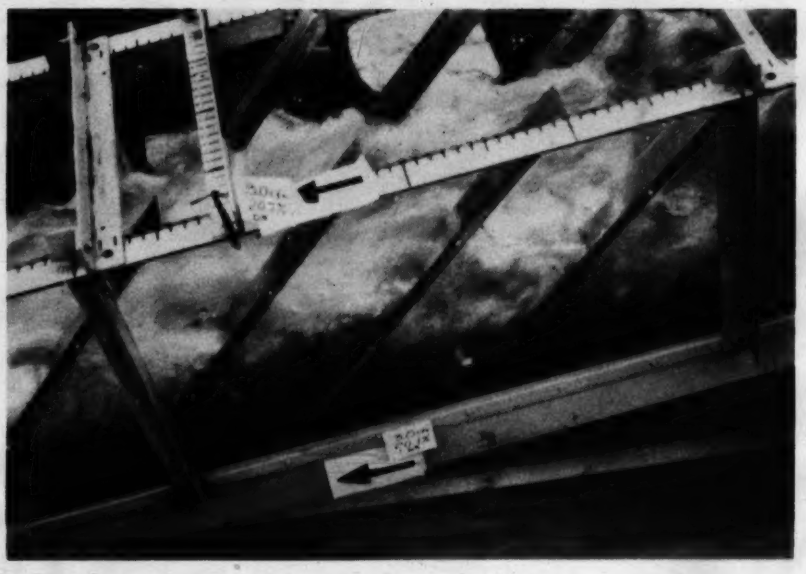


PLATE 34. Denil 3 displaying water surface wave patterns and spiral motions of the lateral streams (experiment 3B3).

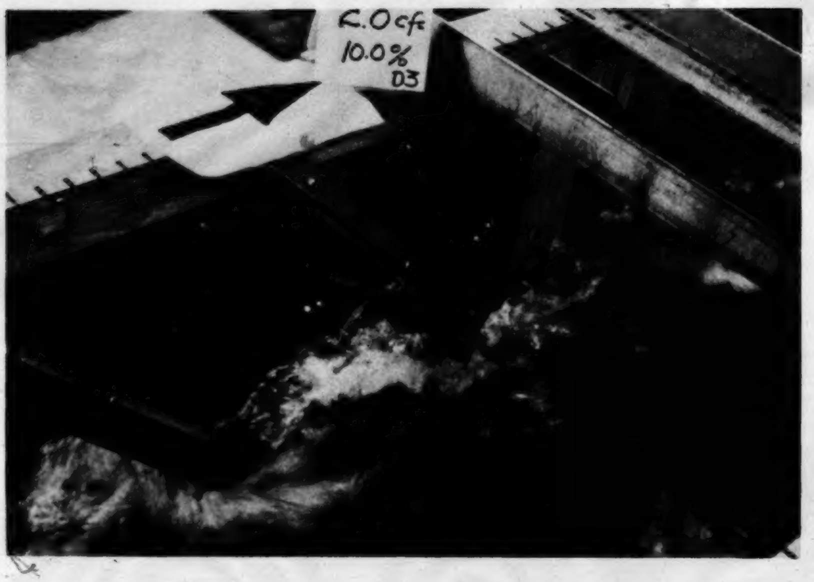


PLATE 35. Denil 3 showing the effect of lateral streams at a slope of 10.0% and a discharge of 56.6 L/s (experiment 3A2).

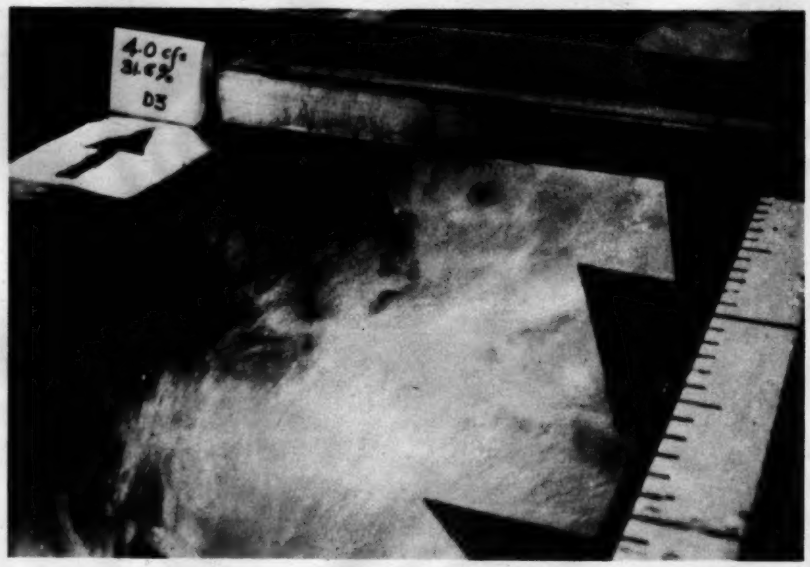


PLATE 36. Denil 3 displaying very strong lateral streams at a slope of 31.5% and a discharge of 113.3 L/s (experiment 3C4).

PLATE 37. Denil 3 displaying spiral motions of the lateral streams near the water surface and inward motion near the flume bottom (discharge 113.3 L/s, experiment 3C4).

PLATE 38. Denil 3 displaying spiral motions of the lateral streams near the water surface and inward motion near the flume bottom (discharge 85.0 L/s, experiment 3B3).

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APPENDIX 1

VELOCITY PROFILES AT NON-CENTRAL NORMALS

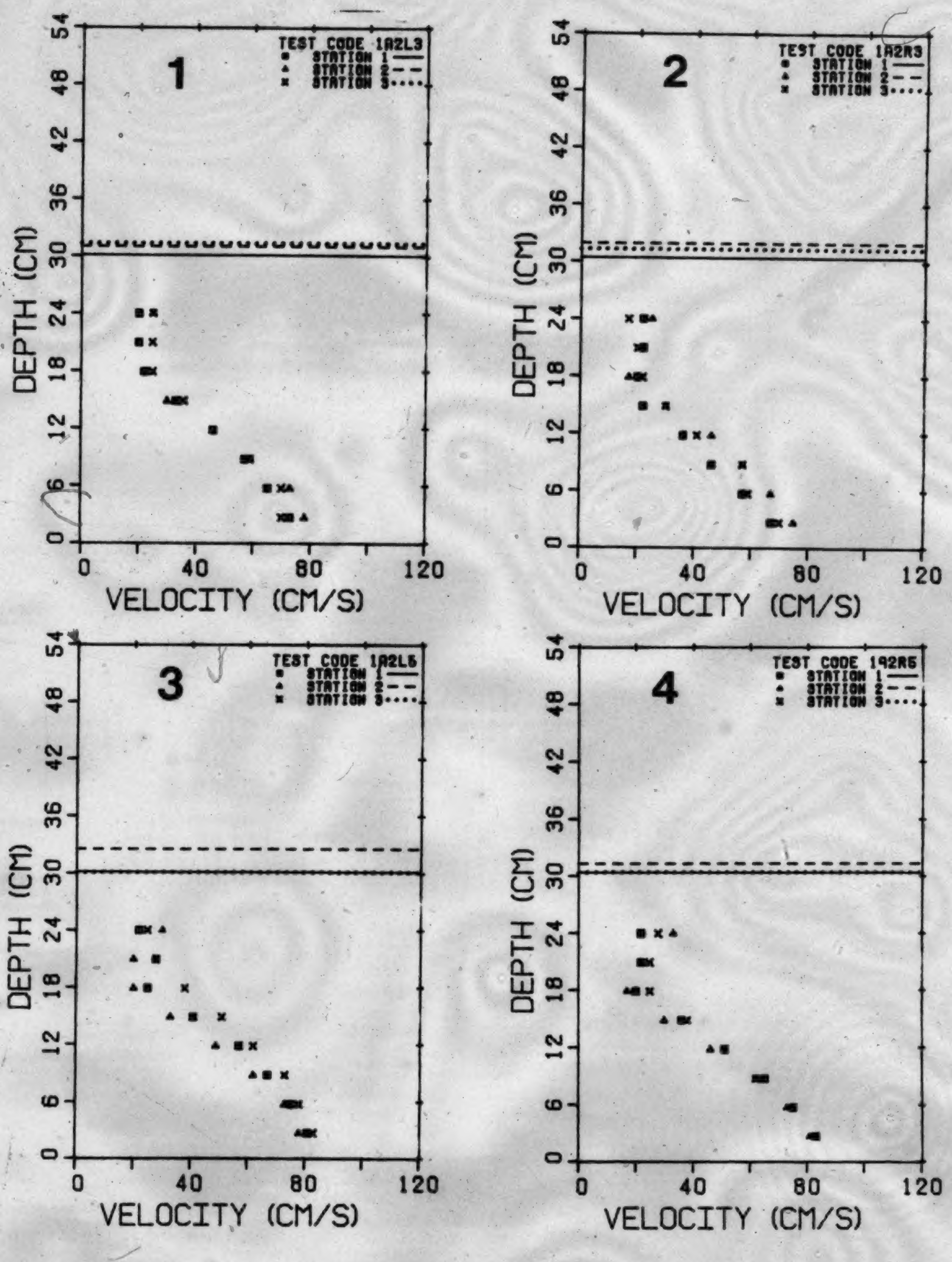
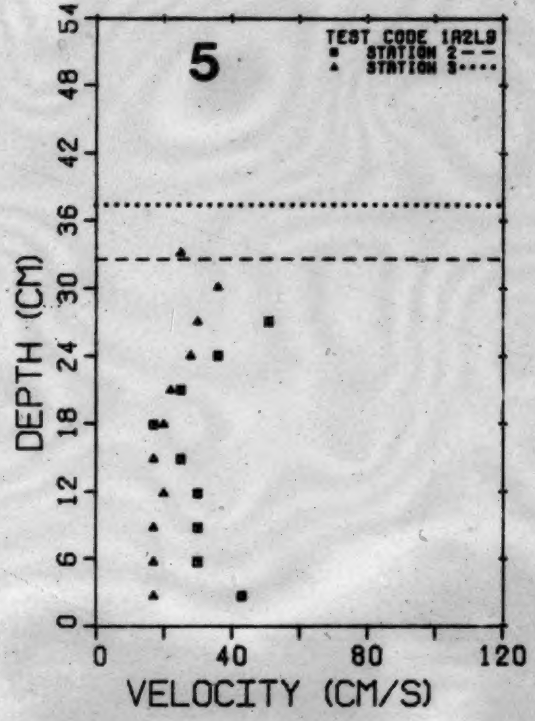


FIG. 1.1. Denil 1: velocity profiles at non-central normals.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▲ STATION 3 ····
DEPTH (CM)
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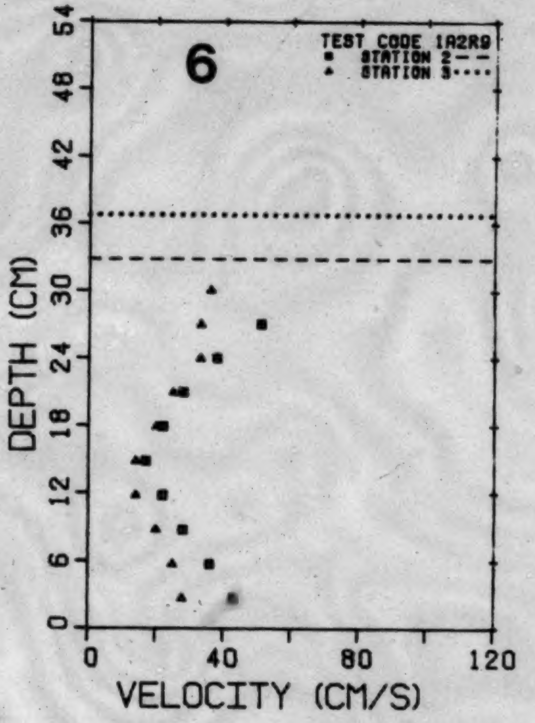
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120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▲ STATION 3 ····
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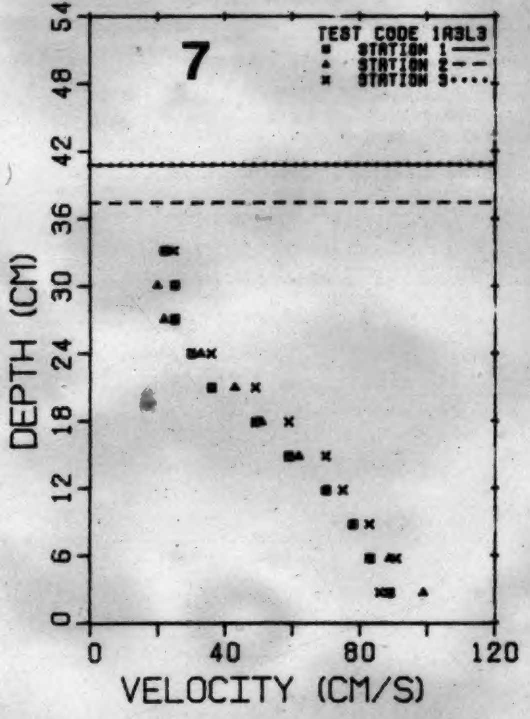
48
54
VELOCITY (CM/S)
0
40
80
120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✖ STATION 3 ····
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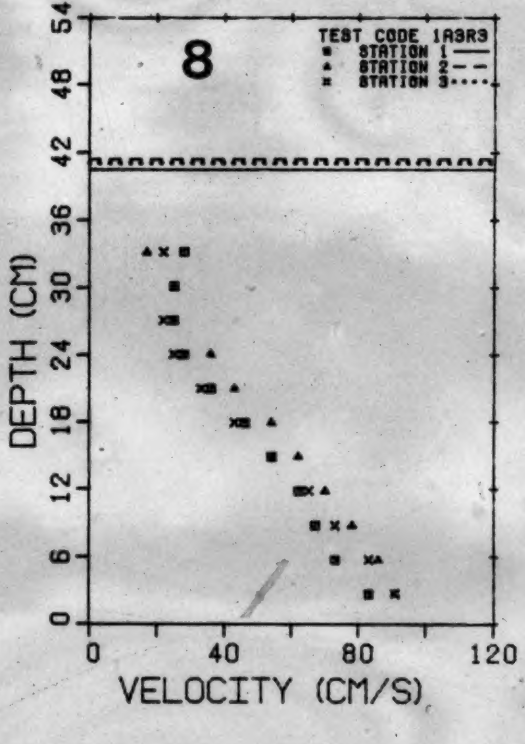
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120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▲ STATION 2 — —
✖ STATION 3 ····
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54
VELOCITY (CM/S)
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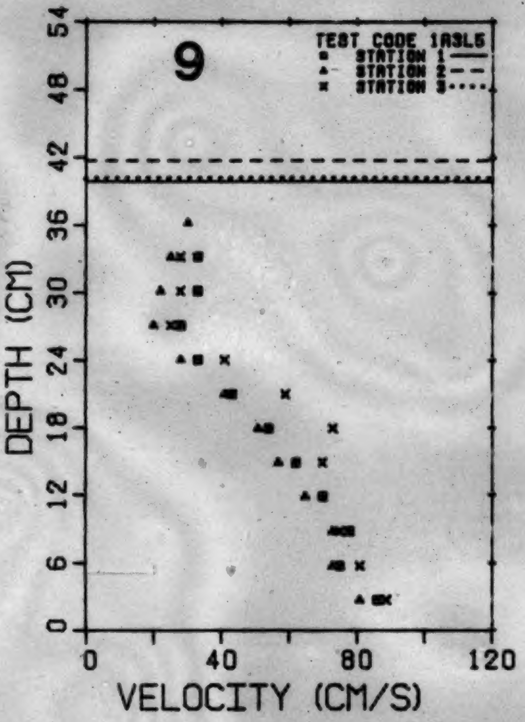
80
120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STATION 2
STATION 3
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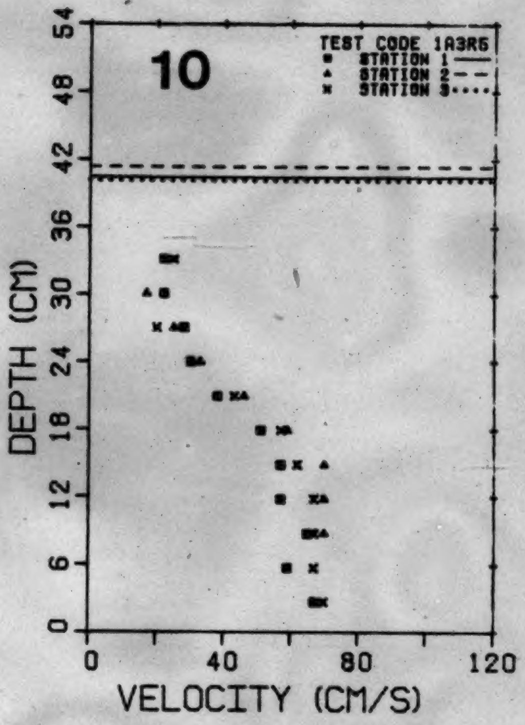
0
40
80
120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STATION 2
STATION 3
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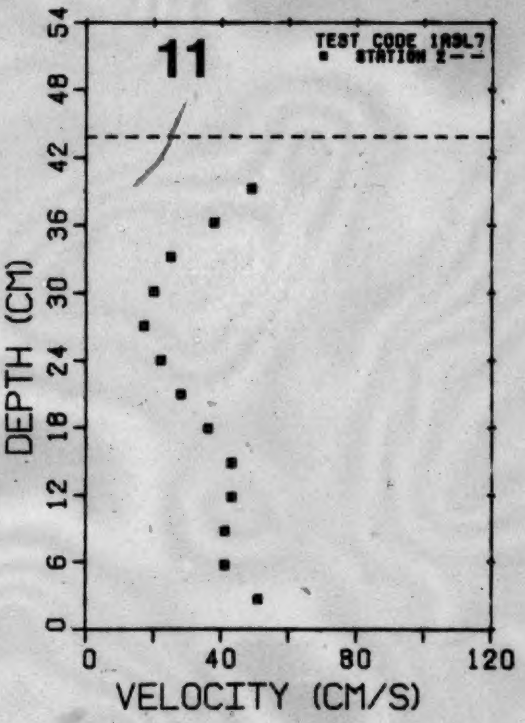
54
VELOCITY (CM/S)
0
40
80
120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VELOCITY (CM/S)
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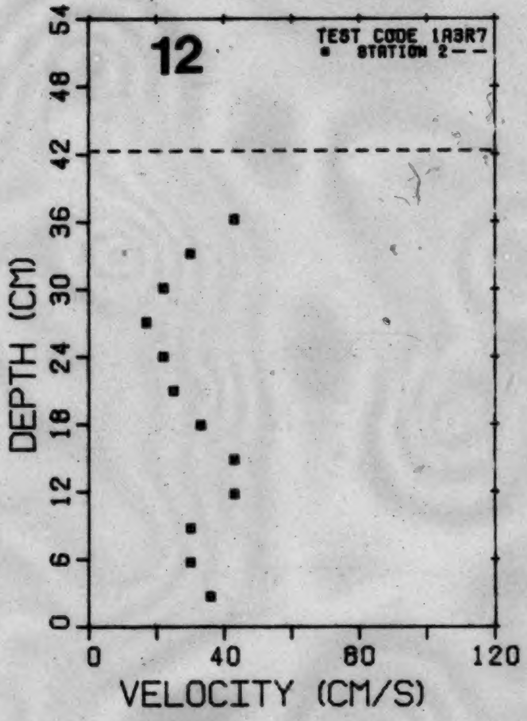
80
120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VELOCITY (CM/S)
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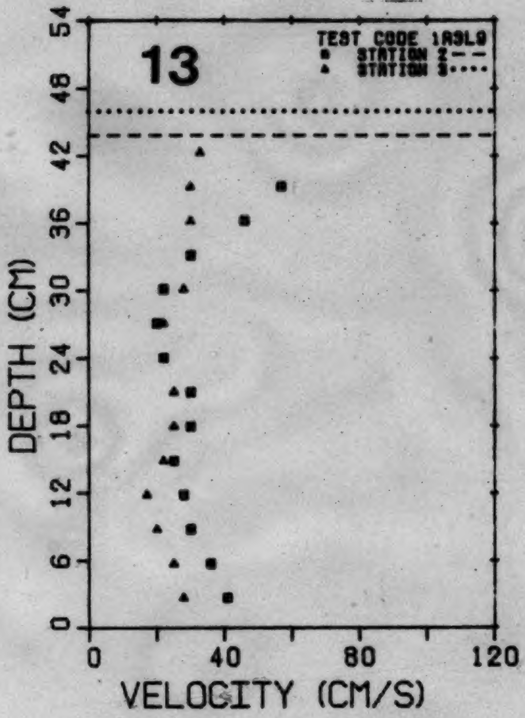
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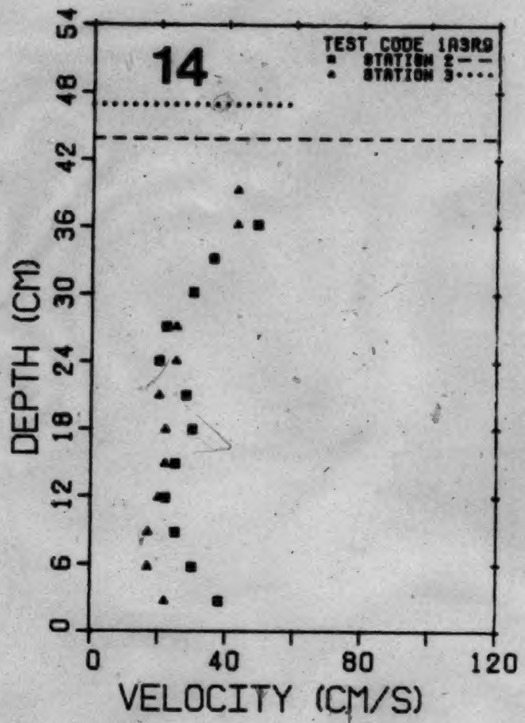
80
120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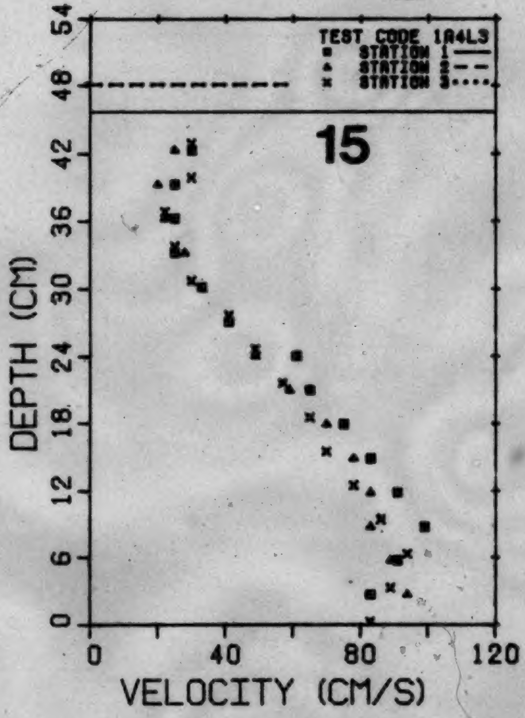
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✕ STATION 3 ····
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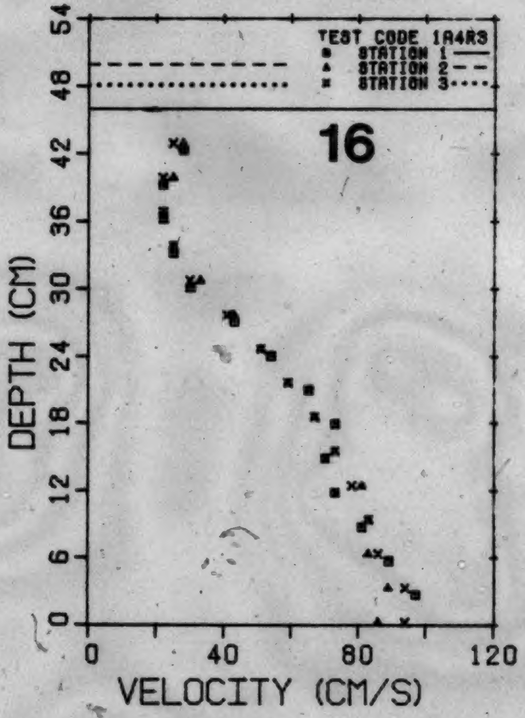
48
54
VELOCITY (CM/S)
0
40
80
120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✕ STATION 3 ····
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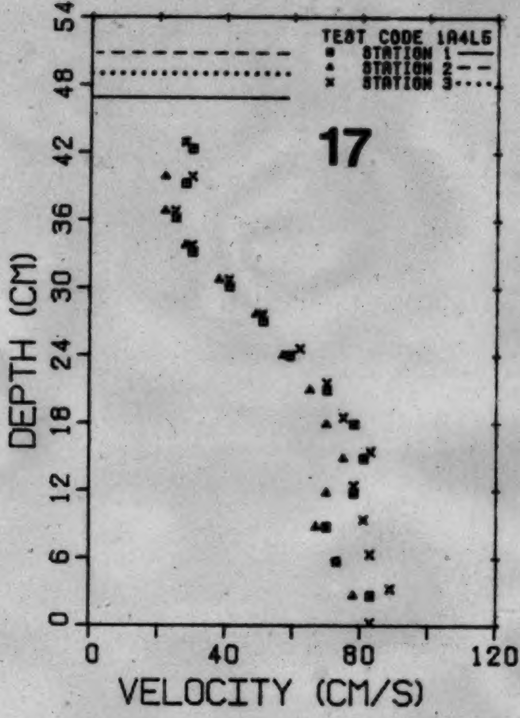
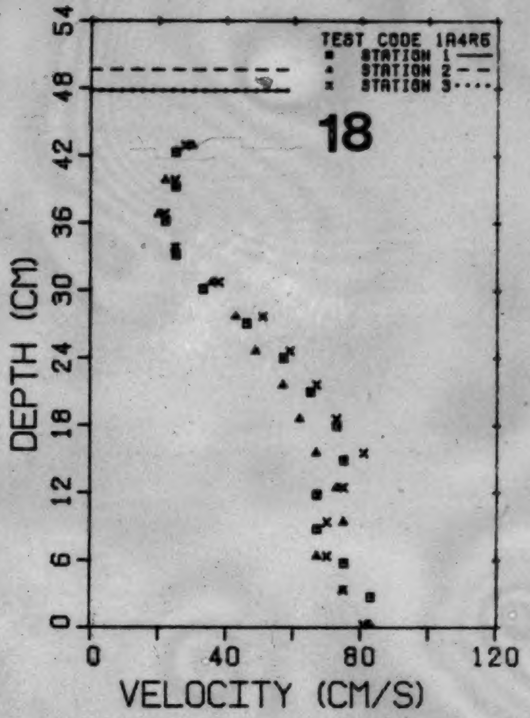
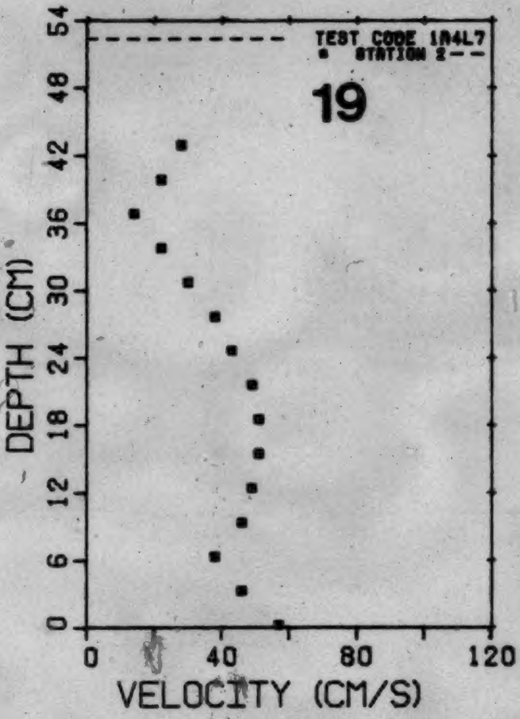
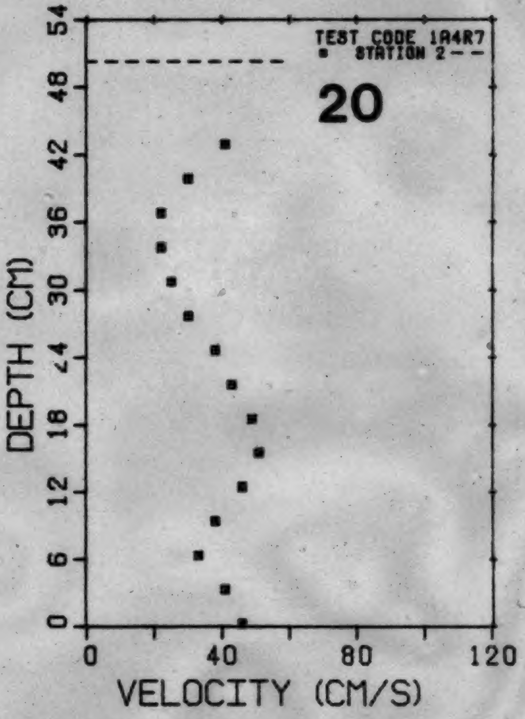
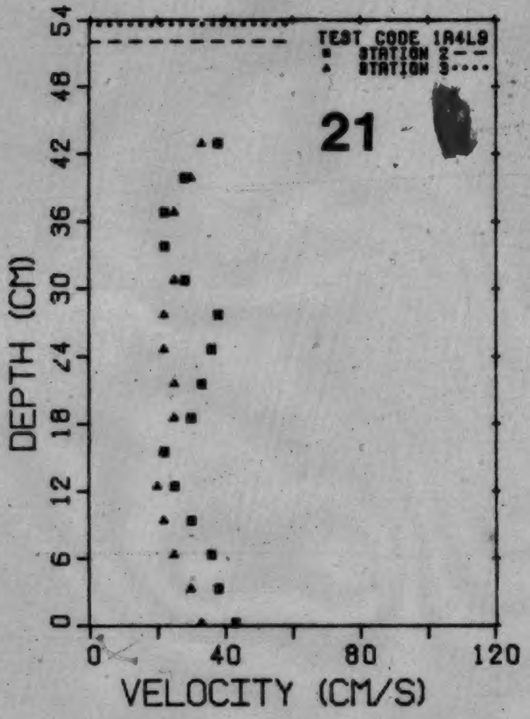
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

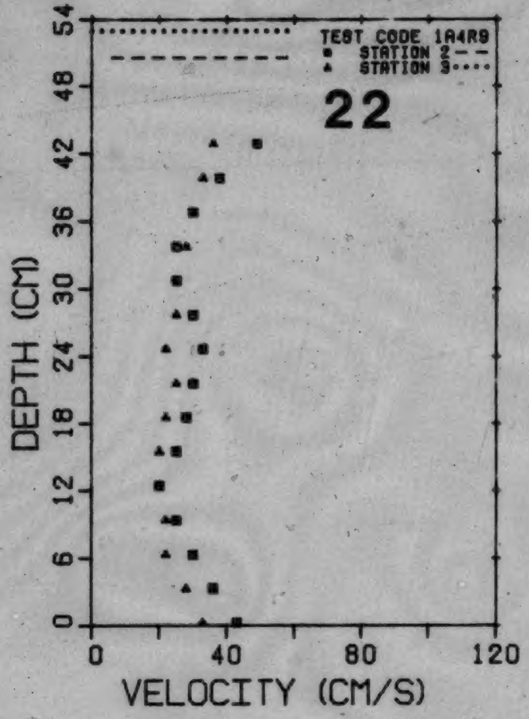

17
TEST CODE 1A4L6
■ STATION 1 —
▲ STATION 2 - -
× STATION 3 ....
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

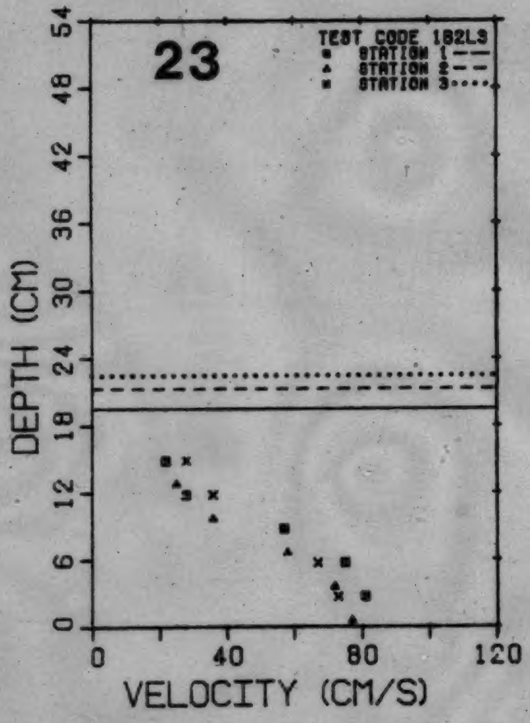

18
TEST CODE 1A4R6
■ STATION 1 —
▲ STATION 2 - -
× STATION 3 ....
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

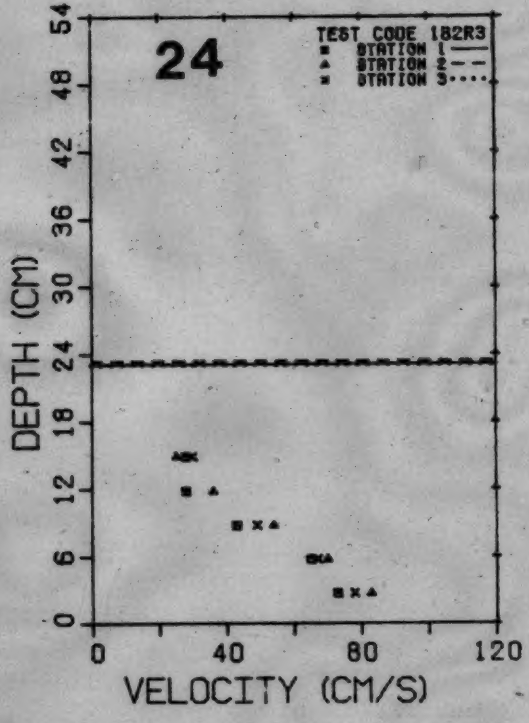

19
TEST CODE 1A4L7
■ STATION 2 - -
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

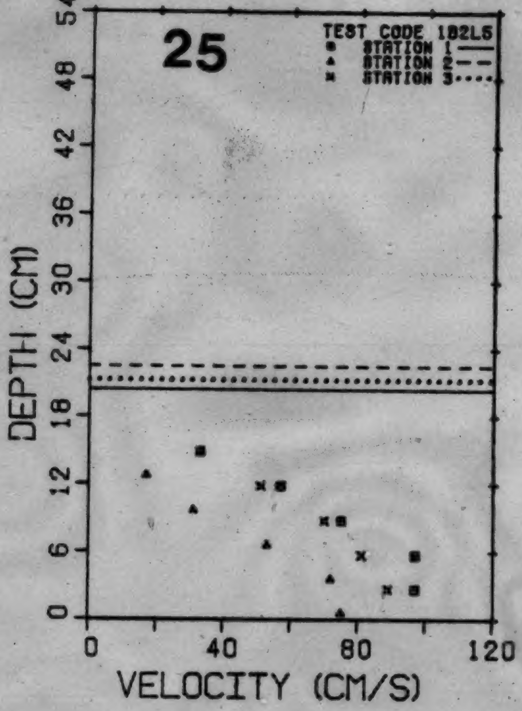

20
TEST CODE 1A4R7
■ STATION 2 - -
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

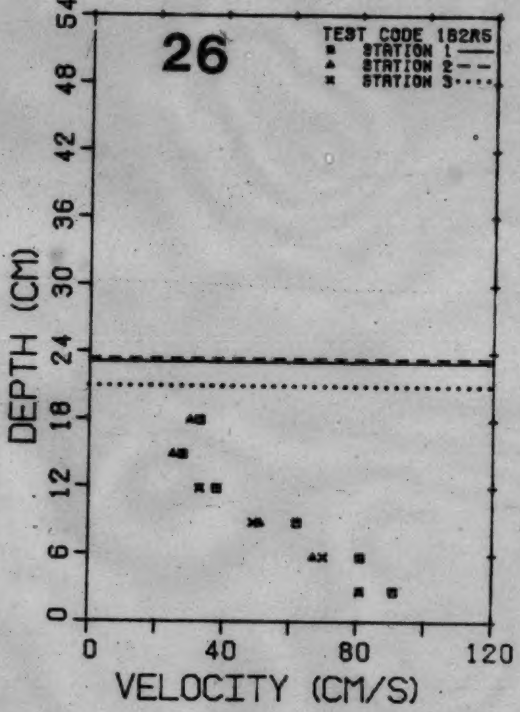

21
TEST CODE 1A4L9
■ STATION 2 - -
▲ STATION 3 ····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

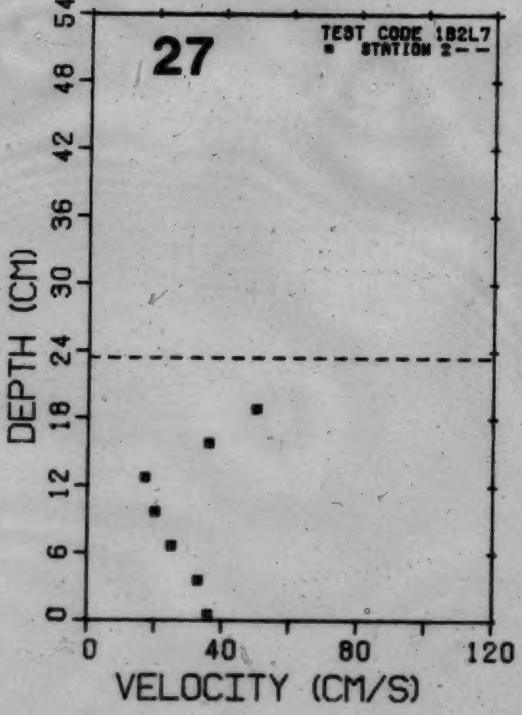

22
TEST CODE 1A4R9
■ STATION 2 - -
▲ STATION 3 ····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

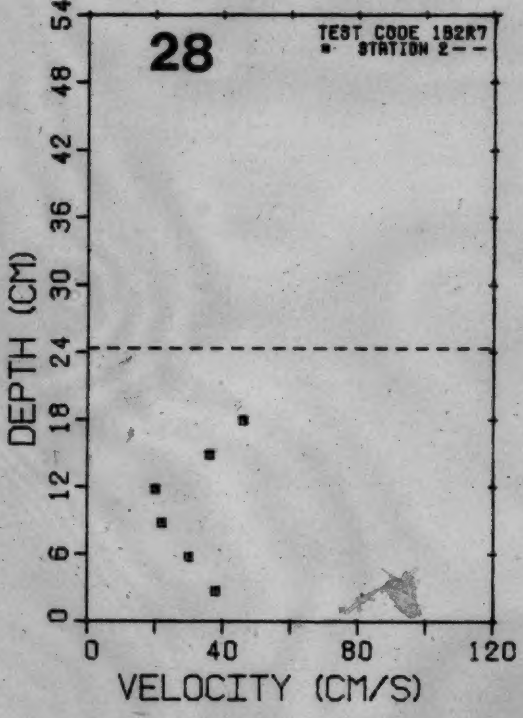

23
TEST CODE 1B2L3
■ STATION 1 ——
▲ STATION 2 - -
✖ STATION 3 ····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

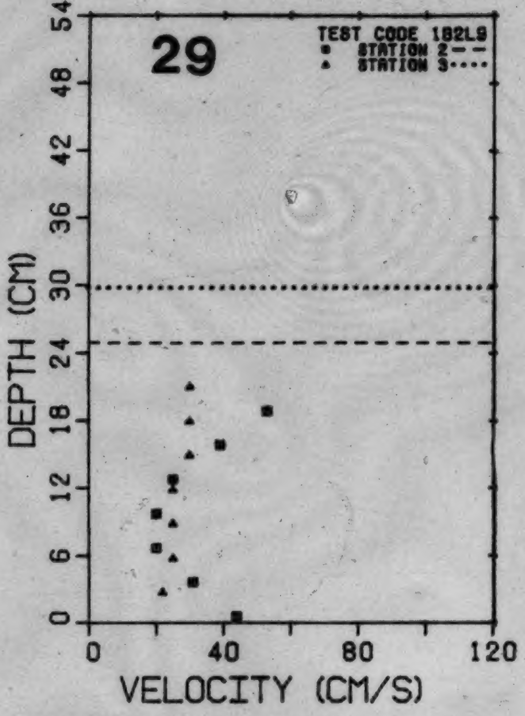

24
TEST CODE 1B2R3
■ STATION 1 ——
▲ STATION 2 - -
✖ STATION 3 ····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

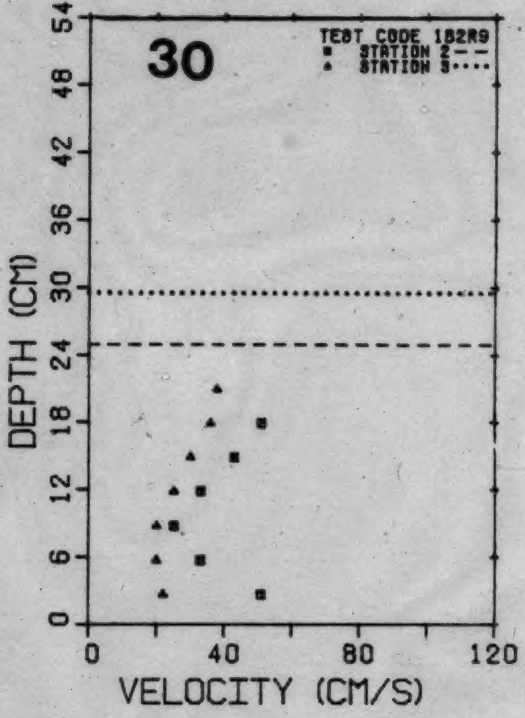

25
TEST CODE 1B2L5
■ STATION 1 ——
▲ STATION 2 – –
✕ STATION 3 ••••
DEPTH (CM)
VELOCITY (CM/S)
0
6
12
18
24
30
36
42
48
54
0
40
80
120

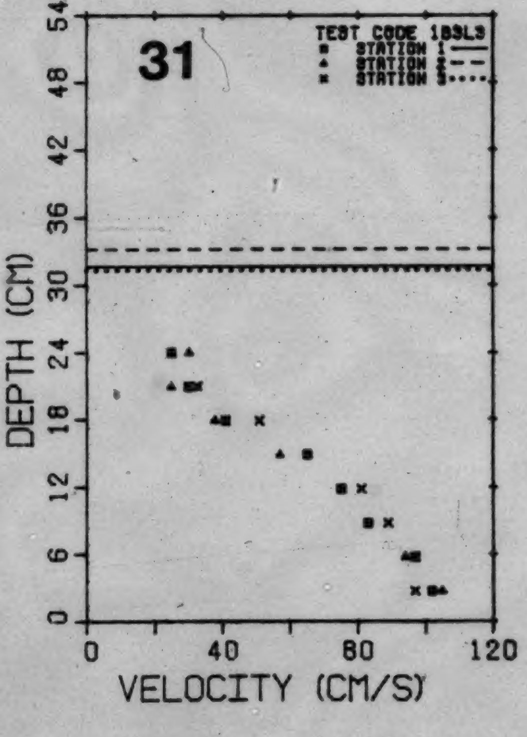

26
TEST CODE 1B2R5
■ STATION 1 ——
▲ STATION 2 – –
✕ STATION 3 ••••
DEPTH (CM)
VELOCITY (CM/S)
0
6
12
18
24
30
36
42
48
54
0
40
80
120

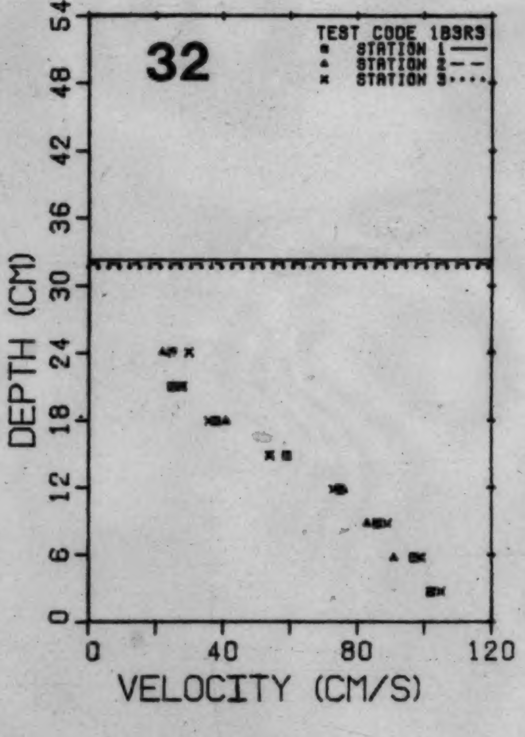

27
TEST CODE 1B2L7
■ STATION 2 – –
DEPTH (CM)
VELOCITY (CM/S)
0
6
12
18
24
30
36
42
48
54
0
40
80
120

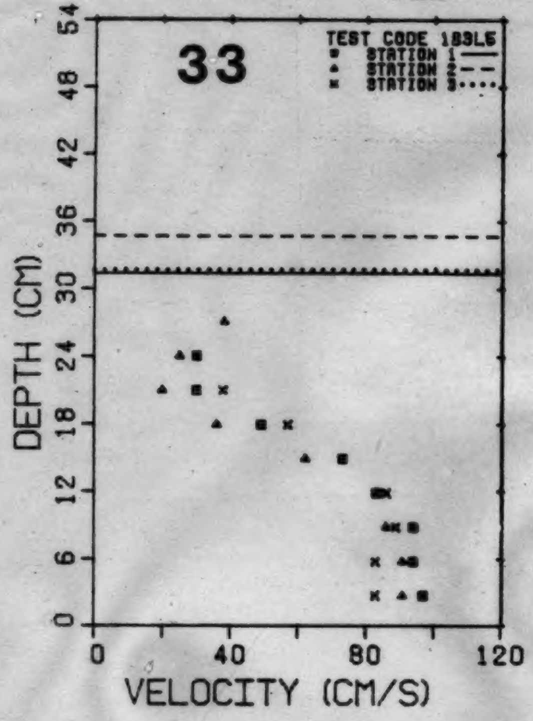

28
TEST CODE 1B2R7
■ STATION 2 – –
DEPTH (CM)
VELOCITY (CM/S)
0
6
12
18
24
30
36
42
48
54
0
40
80
120

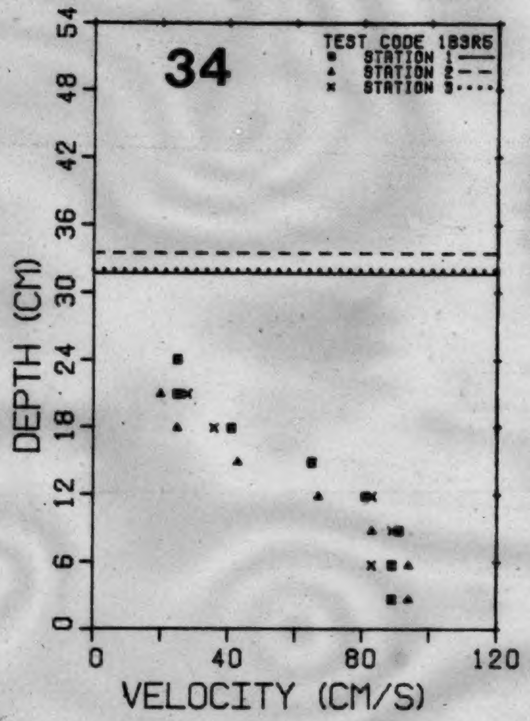

29
TEST CODE 1B2L9
■ STATION 2 – –
▲ STATION 3 ····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

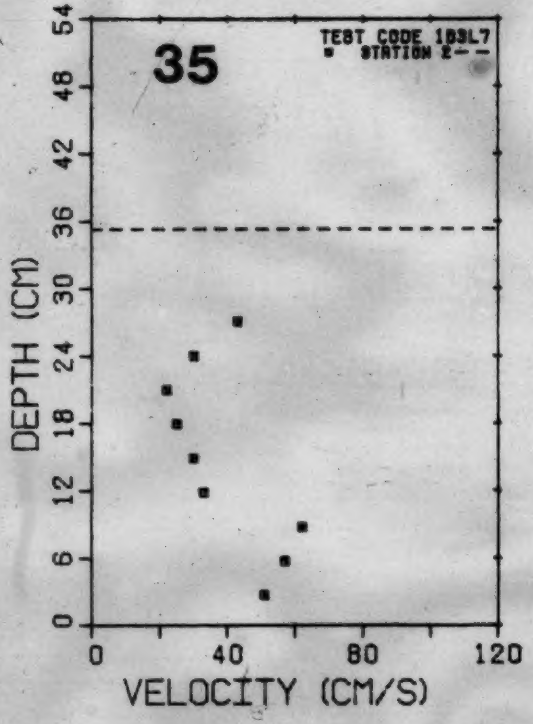

30
TEST CODE 1B2R9
■ STATION 2 – –
▲ STATION 3 ····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120


31
TEST CODE 1B3L3
■ STATION 1 —
▲ STATION 2 – –
× STATION 3 ····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120


32
TEST CODE 1B3R3
■ STATION 1 —
▲ STATION 2 – –
× STATION 3 ····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120


33
TEST CODE 1B3L6
■ STATION 1 ——
▲ STATION 2 - -
× STATION 3 ····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120


34
TEST CODE 1B3R6
■ STATION 1 ——
▲ STATION 2 - -
× STATION 3 ····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120


35
TEST CODE 1B3L7
■ STATION 2 - -
DEPTH (CM)
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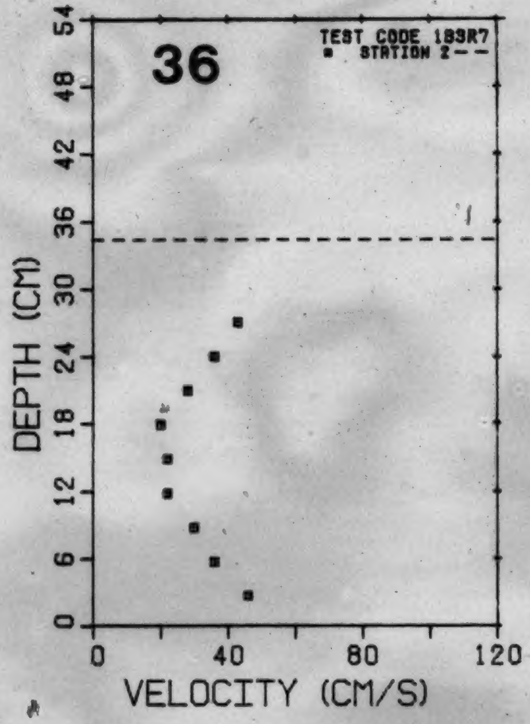
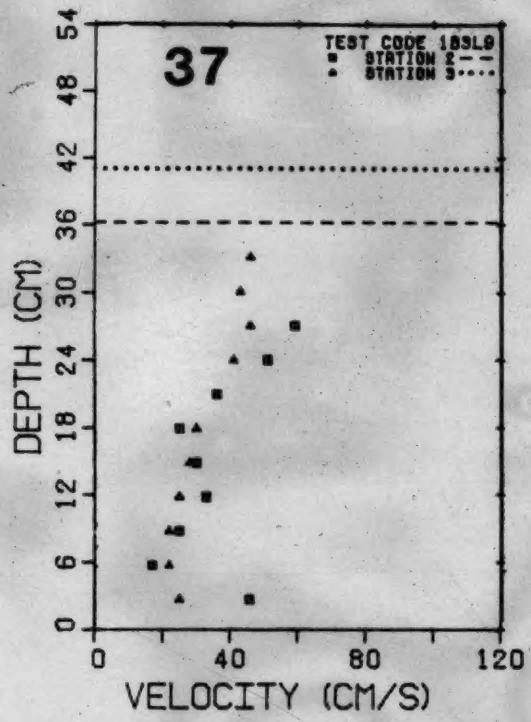
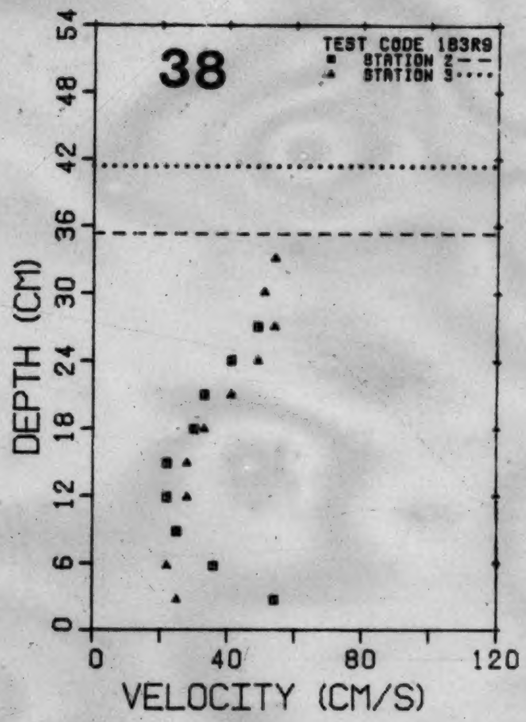
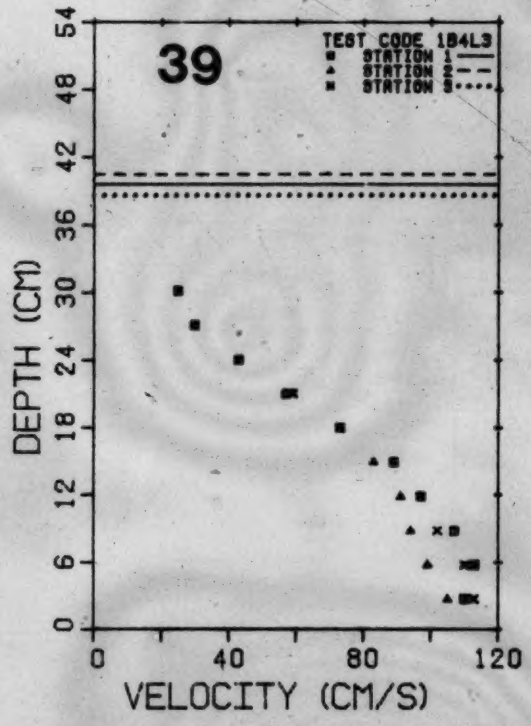
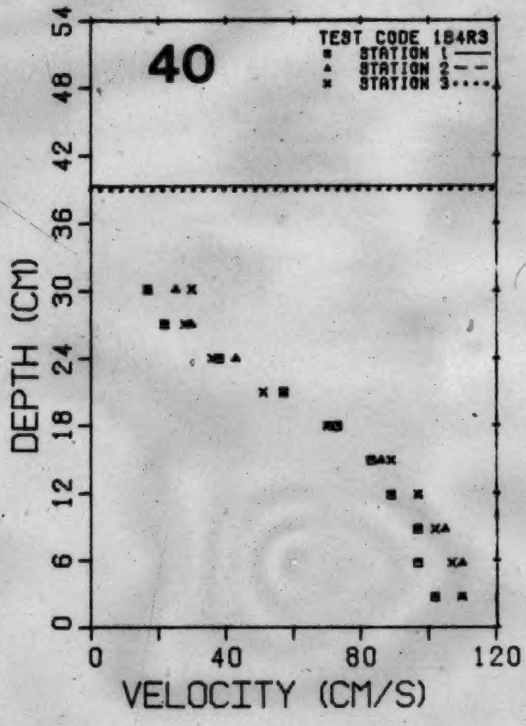
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

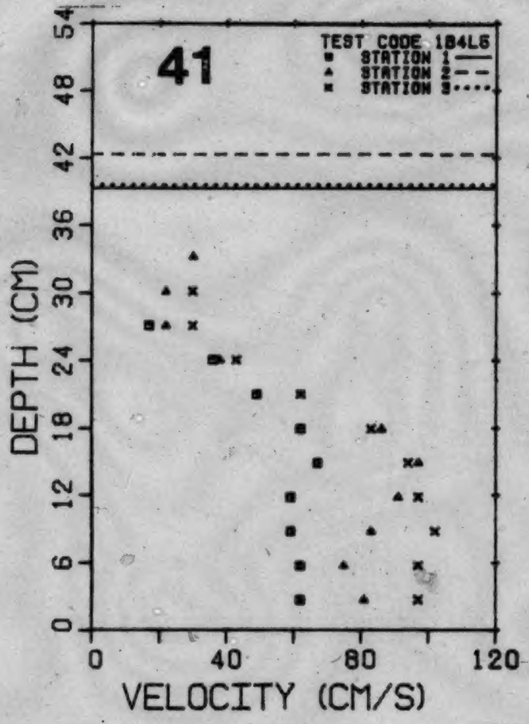

36
TEST CODE 1B3R7
■ STATION 2 - -
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

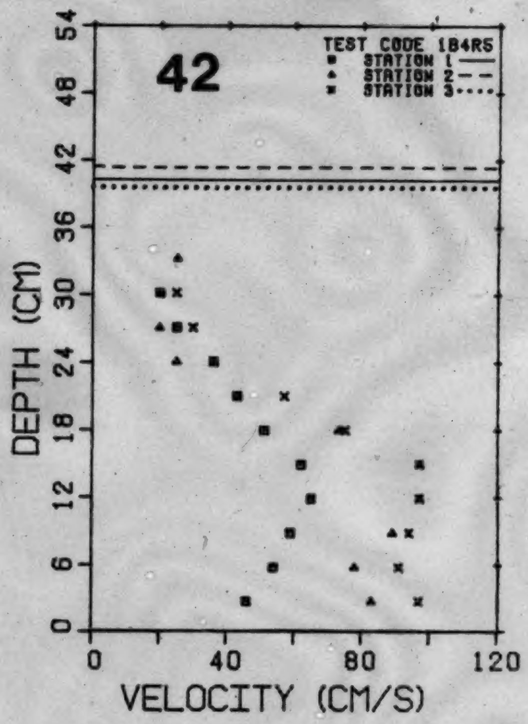

37
TEST CODE 1B3L9
■ STATION 2 – –
▲ STATION 3 ····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

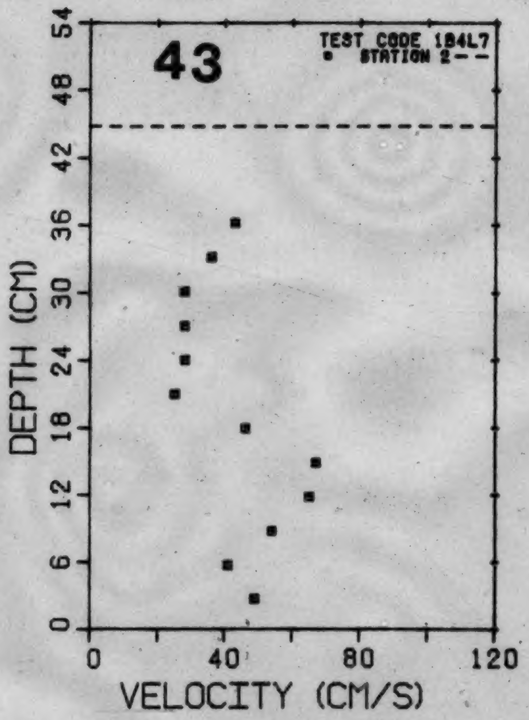

38
TEST CODE 1B3R9
■ STATION 2 – –
▲ STATION 3 ····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

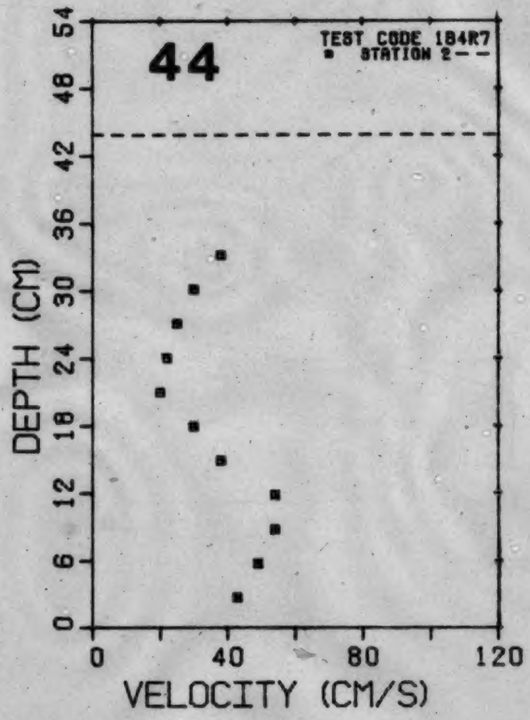

39
TEST CODE 1B4L3
■ STATION 1 ——
▲ STATION 2 – –
✖ STATION 3 ····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

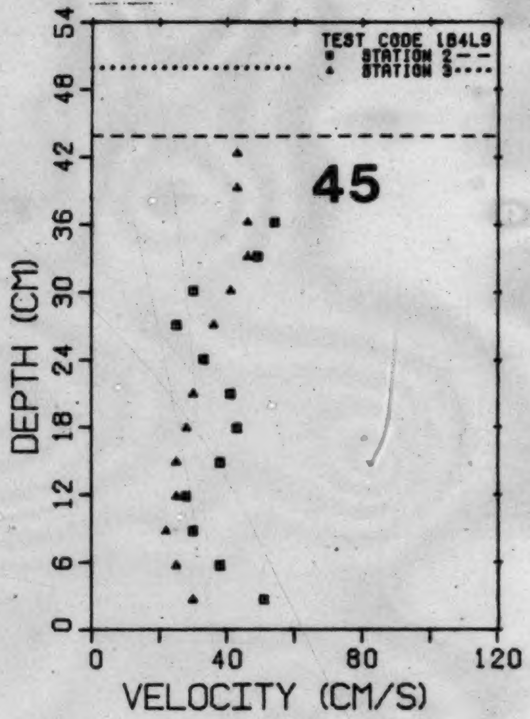

40
TEST CODE 1B4R3
■ STATION 1 ——
▲ STATION 2 – –
× STATION 3 ····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

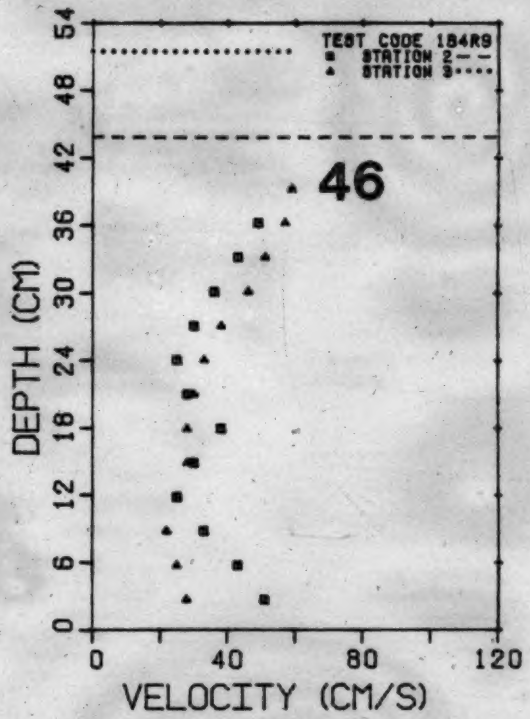

41
TEST CODE 1B4L6
■ STATION 1 ——
▲ STATION 2 – –
✖ STATION 3 ·····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

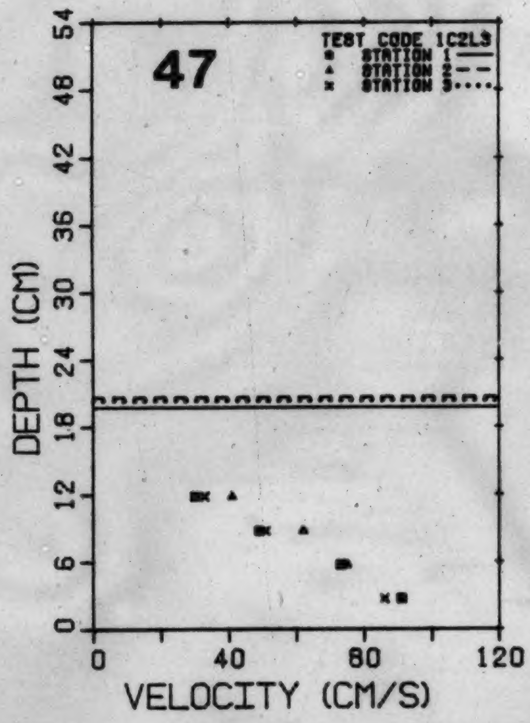

42
TEST CODE 1B4R5
■ STATION 1 ——
▲ STATION 2 – –
✖ STATION 3 ·····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

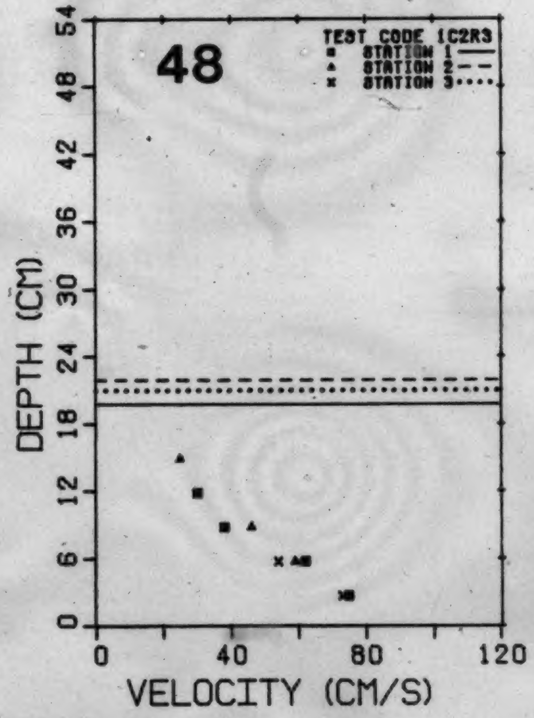

43
TEST CODE 1B4L7
■ STATION 2 – –
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

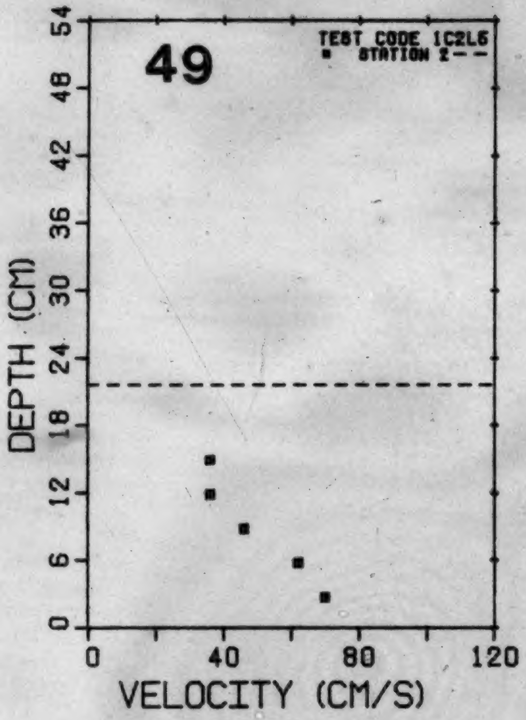

44
TEST CODE 1B4R7
■ STATION 2 – –
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

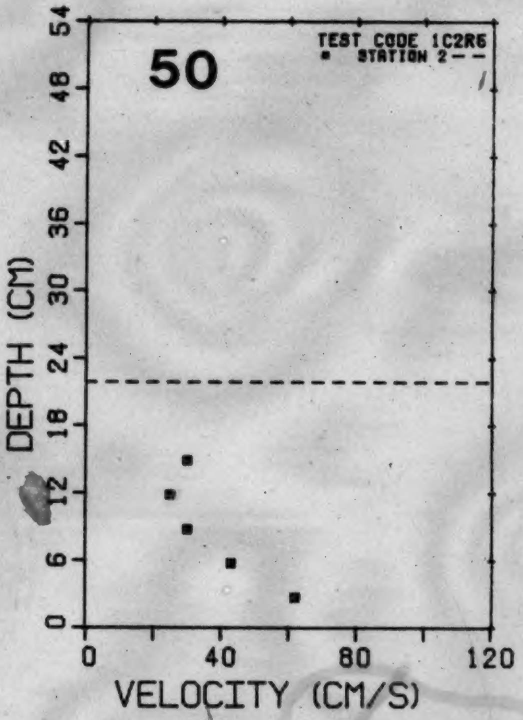

45
TEST CODE 1B4L9
STATION 2 — —
STATION 3 ····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

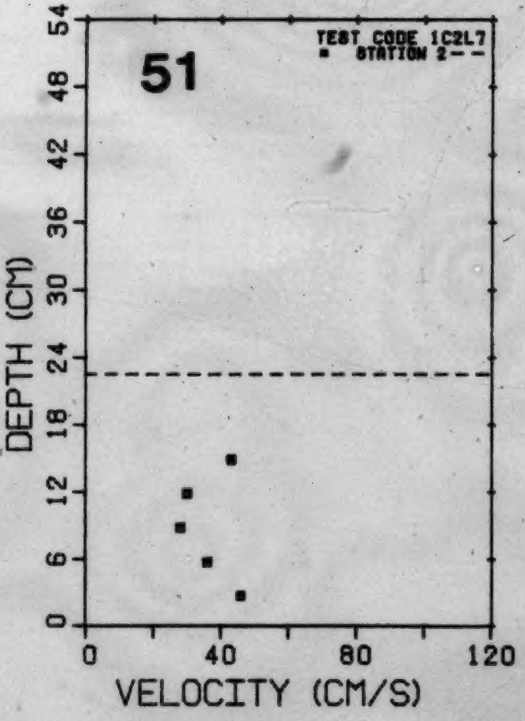

46
TEST CODE 1B4R9
STATION 2 — —
STATION 3 ····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

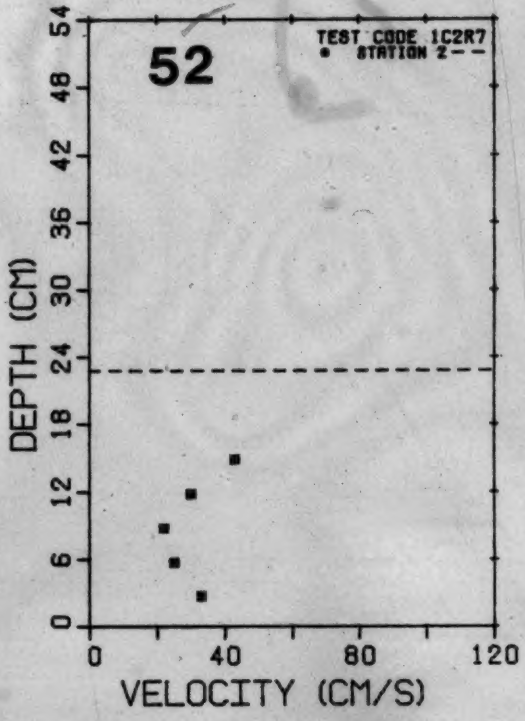

47
TEST CODE 1C2L3
STATION 1 ——
STATION 2 — —
STATION 3 ····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120


48
TEST CODE 1C2R3
STATION 1 ——
STATION 2 — —
STATION 3 ····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

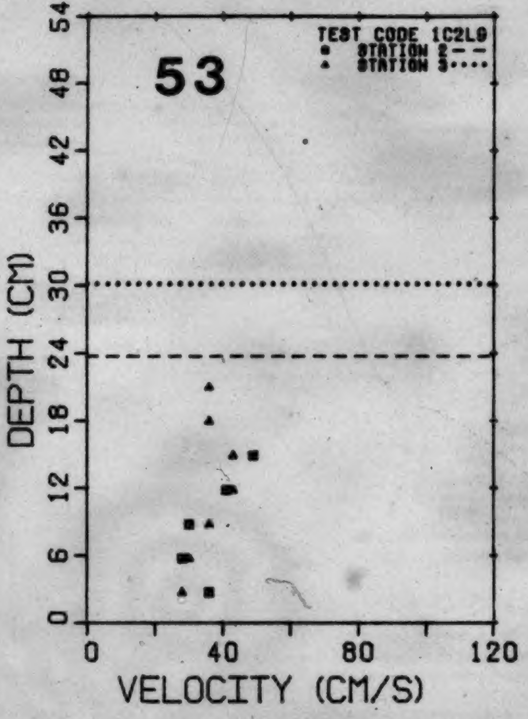

49
TEST CODE 1C2L6
■ STATION 2 - -
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120


50
TEST CODE 1C2R6
■ STATION 2 - -
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

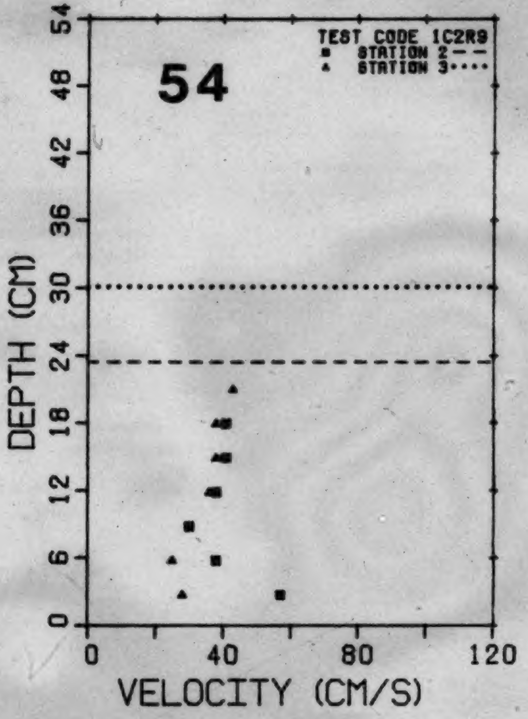

51
TEST CODE 1C2L7
■ STATION 2 - -
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120


52
TEST CODE 1C2R7
■ STATION 2 - -
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

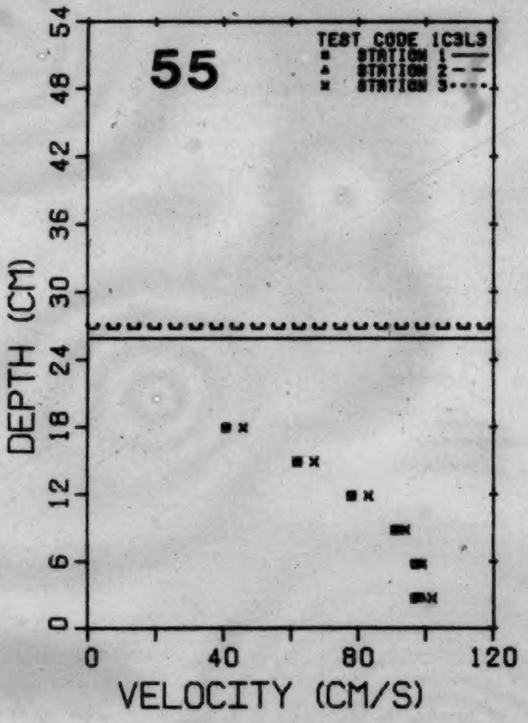
53


TEST CODE 1C2L9
■ STATION 2 — —
▲ STATION 3 ·····
DEPTH (CM)
VELOCITY (CM/S)
0
6
12
18
24
30
36
42
48
54
0
40
80
120

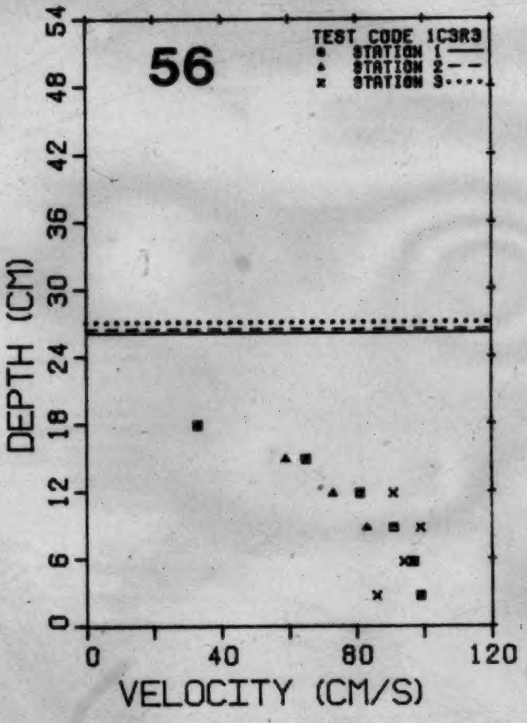
54


TEST CODE 1C2R9
■ STATION 2 — —
▲ STATION 3 ·····
DEPTH (CM)
VELOCITY (CM/S)
0
6
12
18
24
30
36
42
48
54
0
40
80
120

55


TEST CODE 1C3L3
■ STATION 1 ——
▲ STATION 2 — —
✕ STATION 3 ·····
DEPTH (CM)
VELOCITY (CM/S)
0
6
12
18
24
30
36
42
48
54
0
40
80
120

56


TEST CODE 1C3R3
■ STATION 1 ——
▲ STATION 2 — —
✕ STATION 3 ·····
DEPTH (CM)
VELOCITY (CM/S)
0
6
12
18
24
30
36
42
48
54
0
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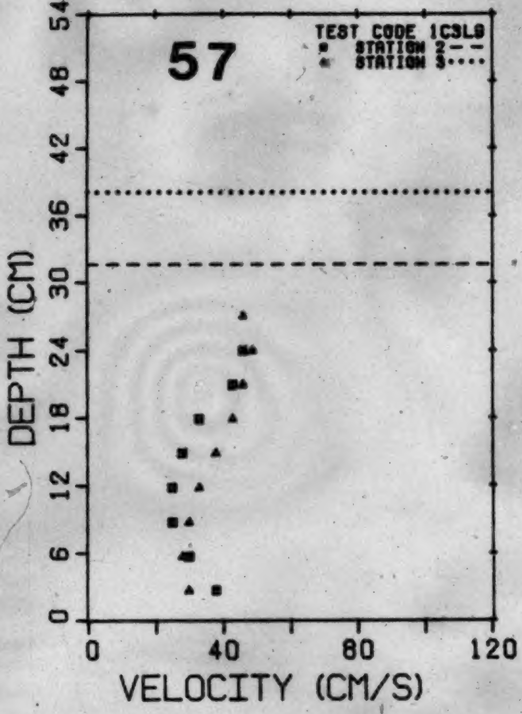
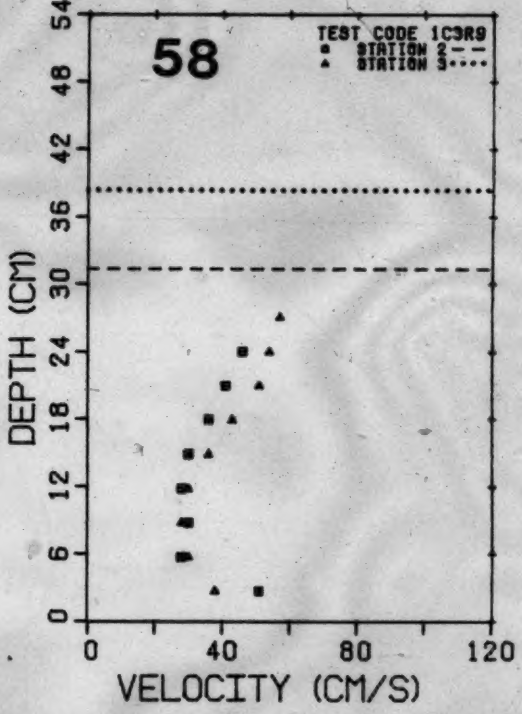
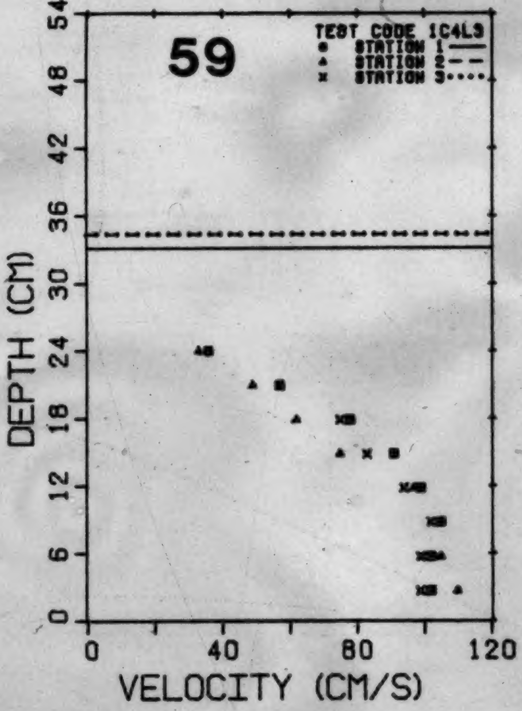
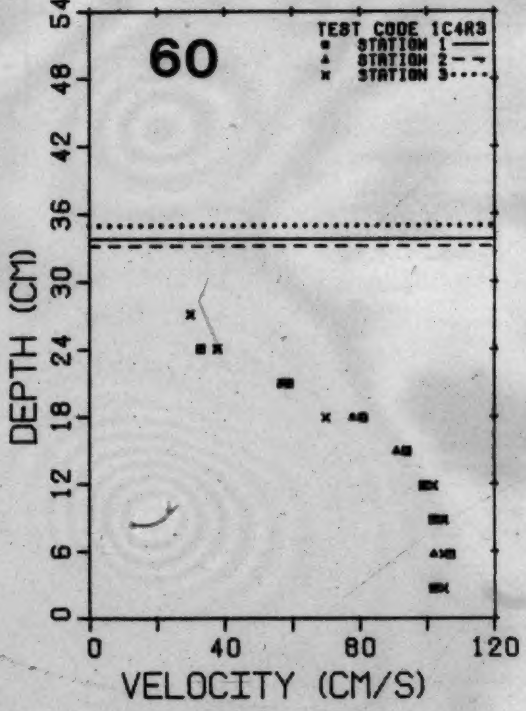
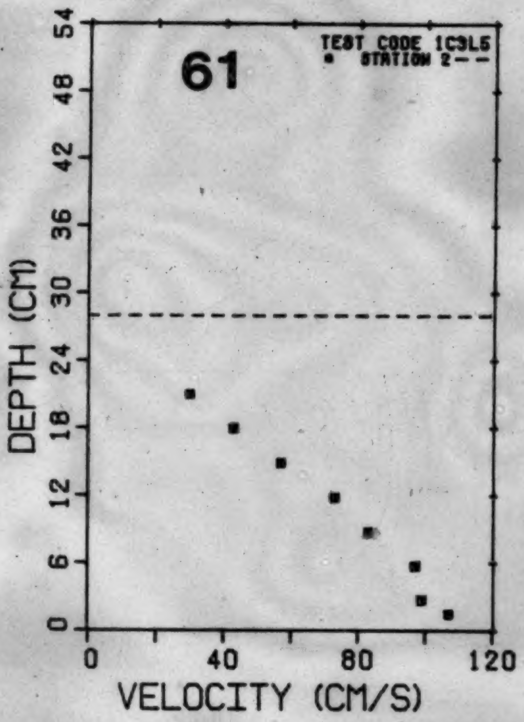
80
120

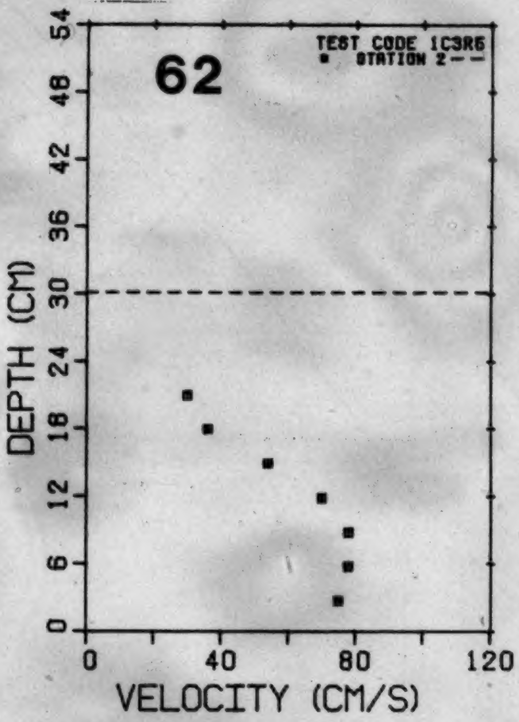

57
TEST CODE 1C3L9
■ STATION 2 — —
▲ STATION 3 ····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

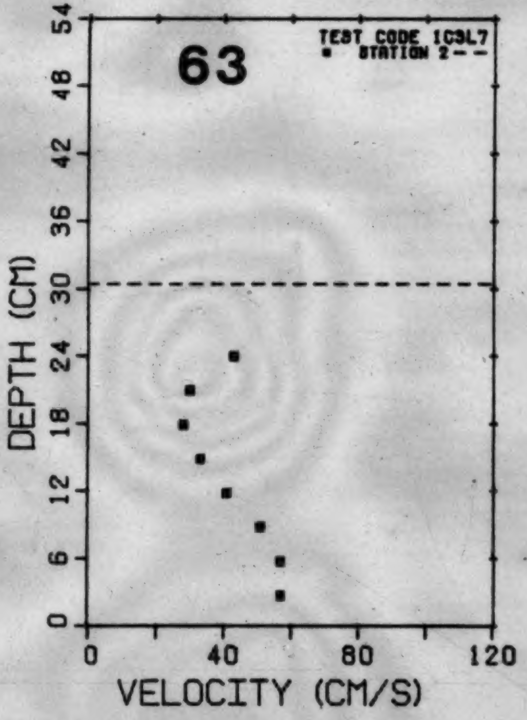

58
TEST CODE 1C3R9
■ STATION 2 — —
▲ STATION 3 ····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

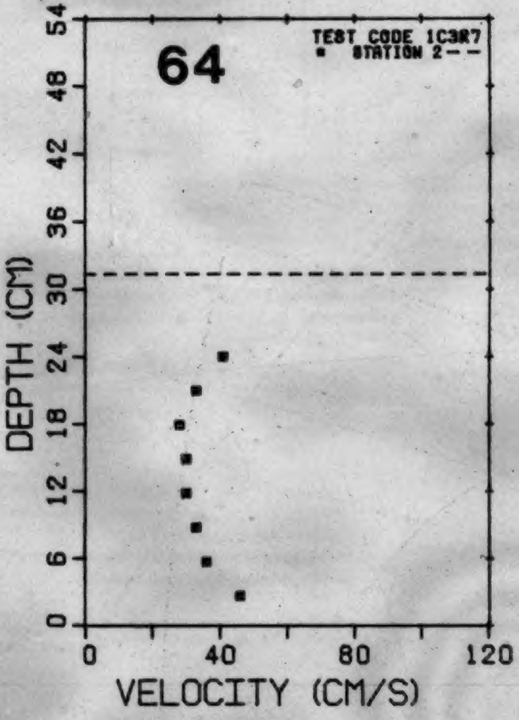

59
TEST CODE 1C4L3
■ STATION 1 ——
▲ STATION 2 — —
× STATION 3 ····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

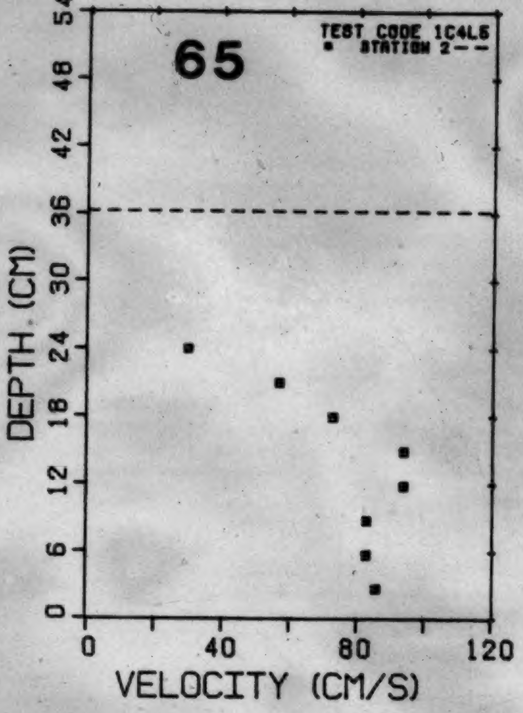

60
TEST CODE 1C4R3
■ STATION 1 ——
▲ STATION 2 — —
× STATION 3 ····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

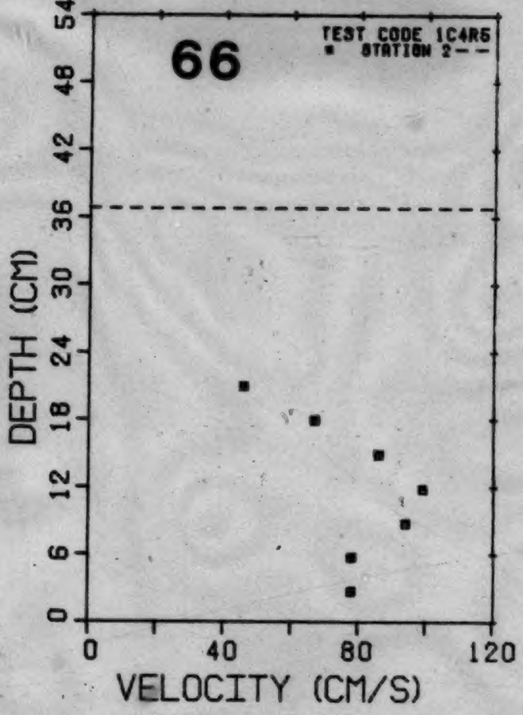

61
TEST CODE 1C3L5
■ STATION 2 - -
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
0
40
80
120
VELOCITY (CM/S)

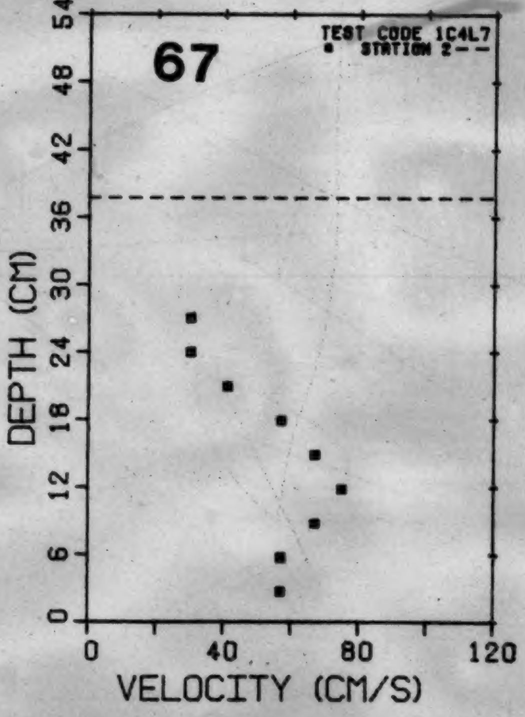

62
TEST CODE 1C3R6
■ STATION 2 - -
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
0
40
80
120
VELOCITY (CM/S)

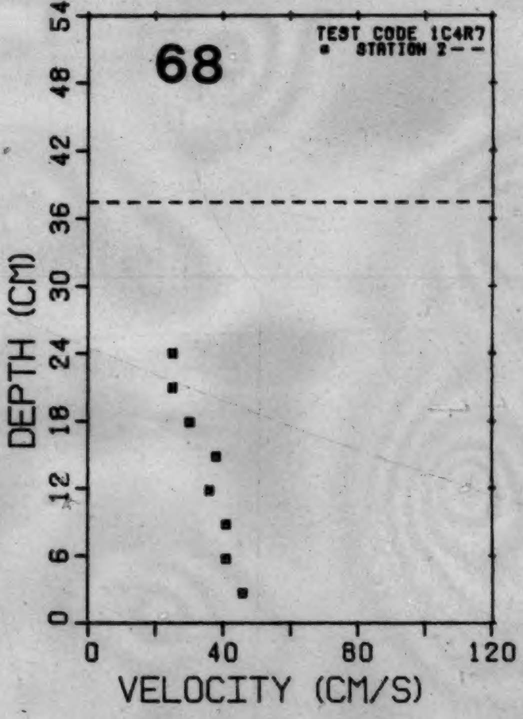

63
TEST CODE 1C3L7
■ STATION 2 - -
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
0
40
80
120
VELOCITY (CM/S)

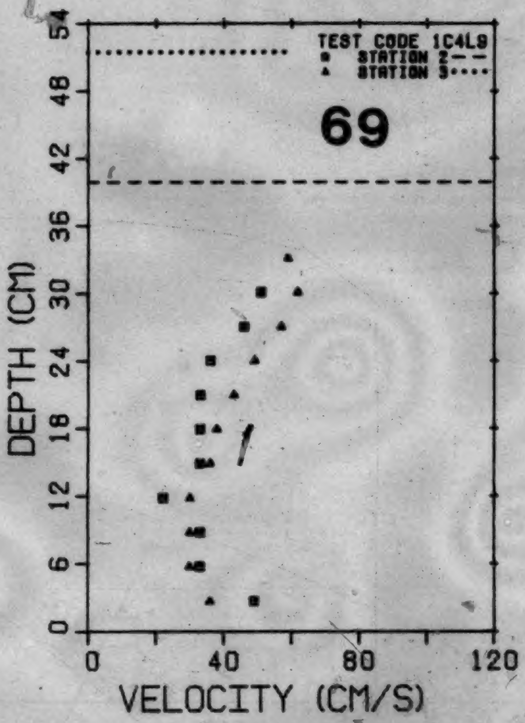

64
TEST CODE 1C3R7
■ STATION 2 - -
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
0
40
80
120
VELOCITY (CM/S)

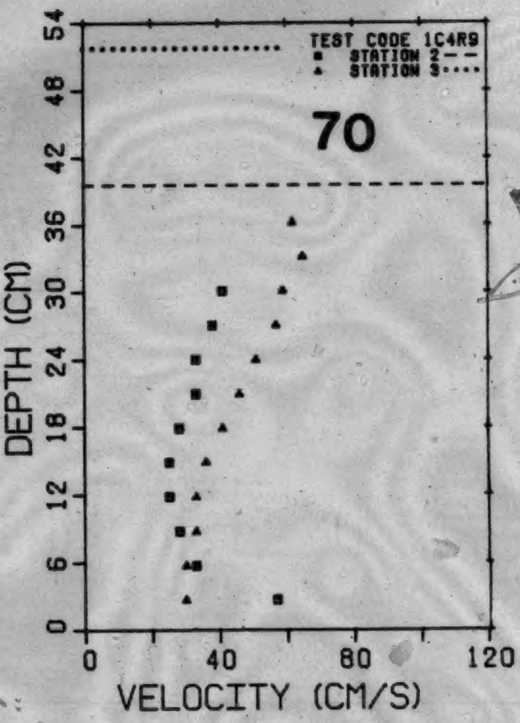

65
TEST CODE 1C4L5
■ STATION 2 - -
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120


66
TEST CODE 1C4R5
■ STATION 2 - -
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120


67
TEST CODE 1C4L7
■ STATION 2 - -
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120


68
TEST CODE 1C4R7
■ STATION 2 - -
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120


TEST CODE 1C4L9
STATION 2
STATION 3
69
DEPTH (CM)
VELOCITY (CM/S)
0
6
12
18
24
30
36
42
48
54
0
40
80
120


TEST CODE 1C4R9
STATION 2
STATION 3
70
DEPTH (CM)
VELOCITY (CM/S)
0
6
12
18
24
30
36
42
48
54
0
40
80
120

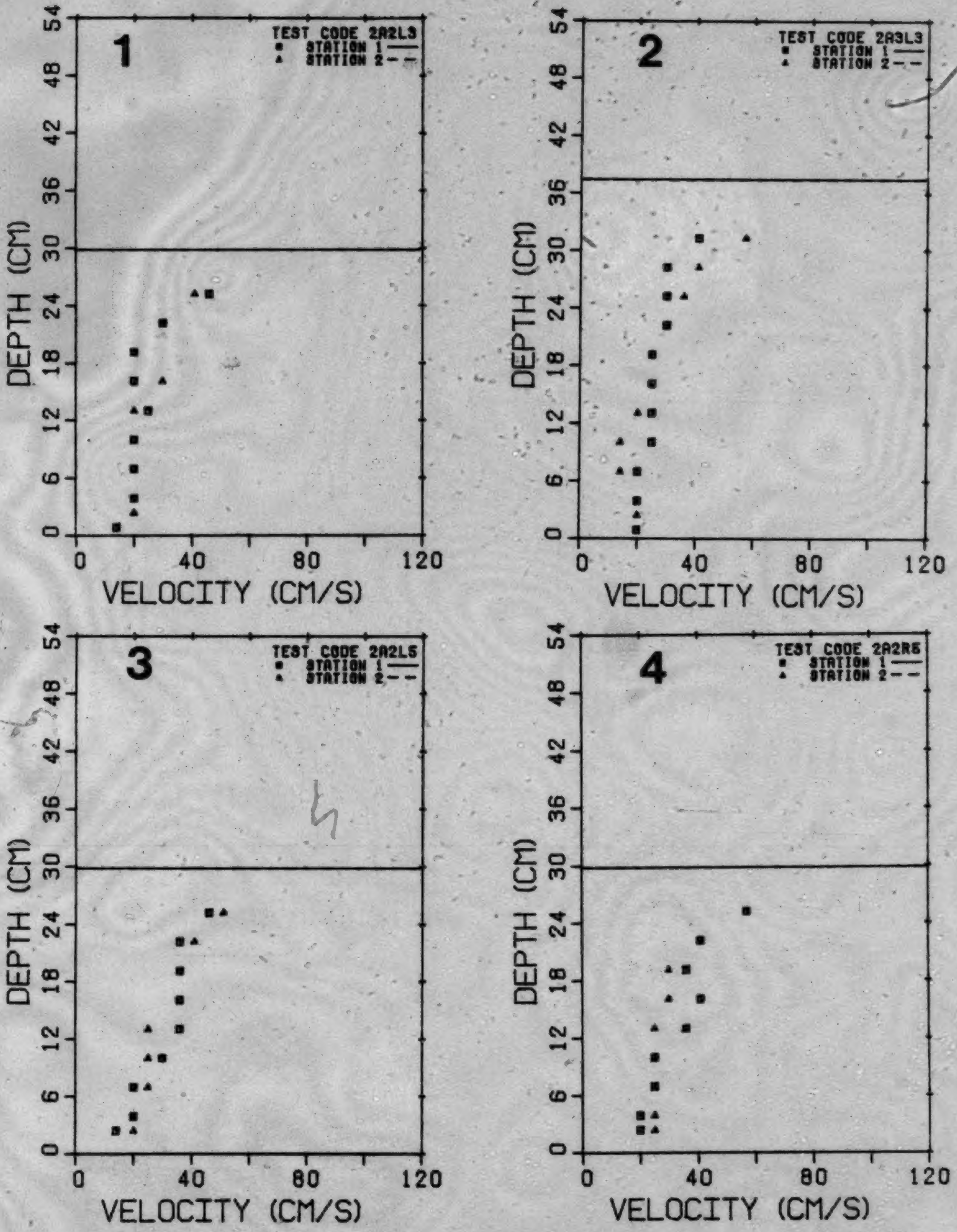
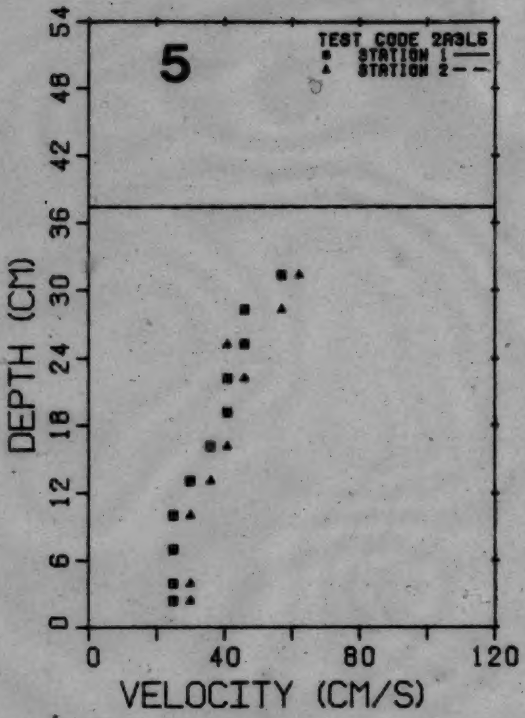
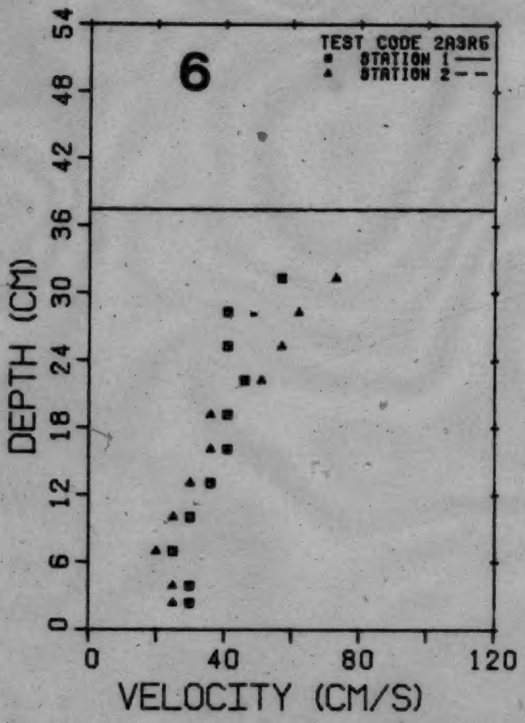
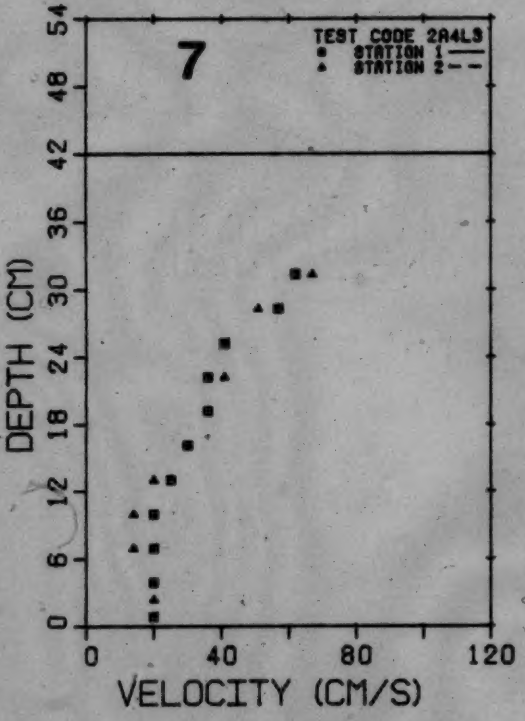
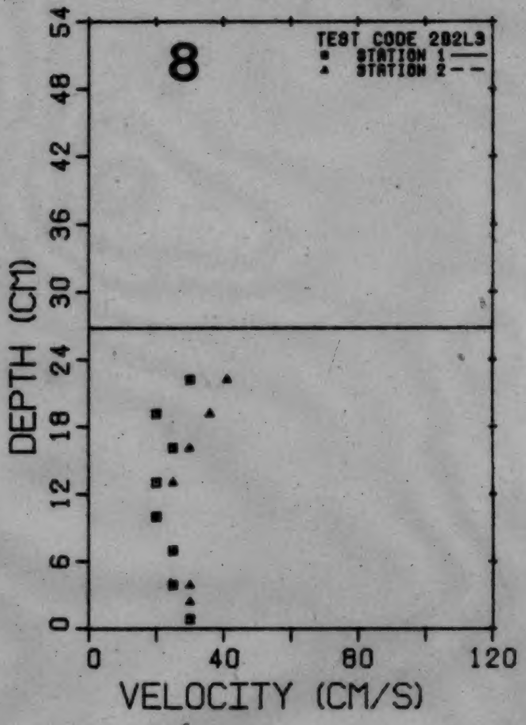


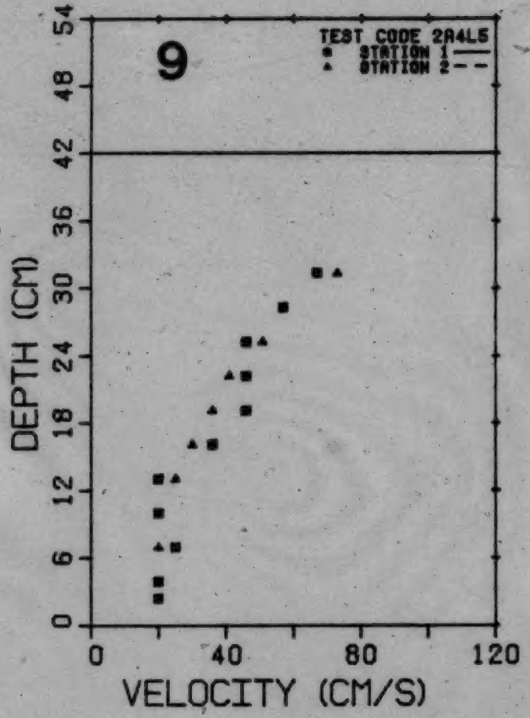
FIG. 1.2. Denil 2: velocity profiles at non-central normals.

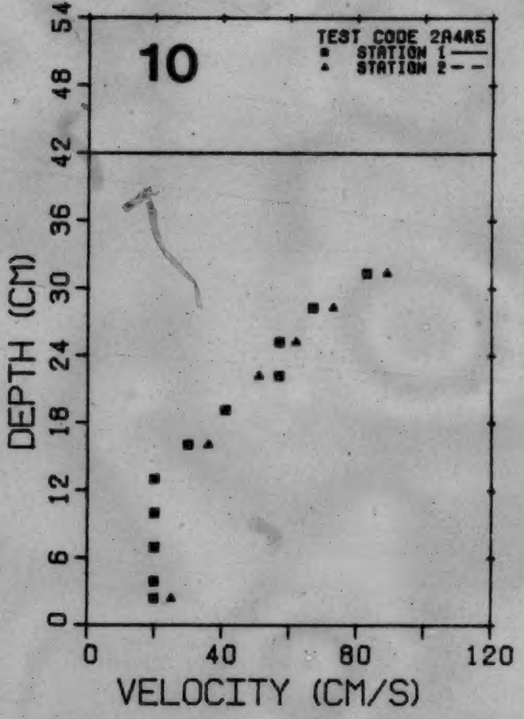

5
TEST CODE 2A3L5
■ STATION 1 ——
▲ STATION 2 – –
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

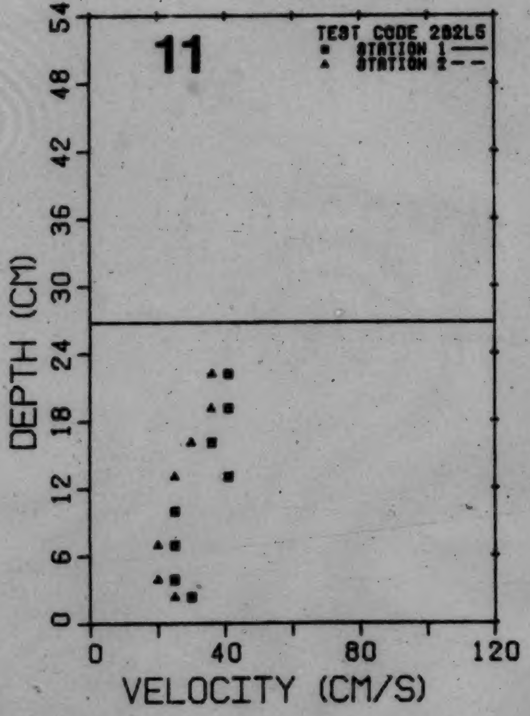

6
TEST CODE 2A3R6
■ STATION 1 ——
▲ STATION 2 – –
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

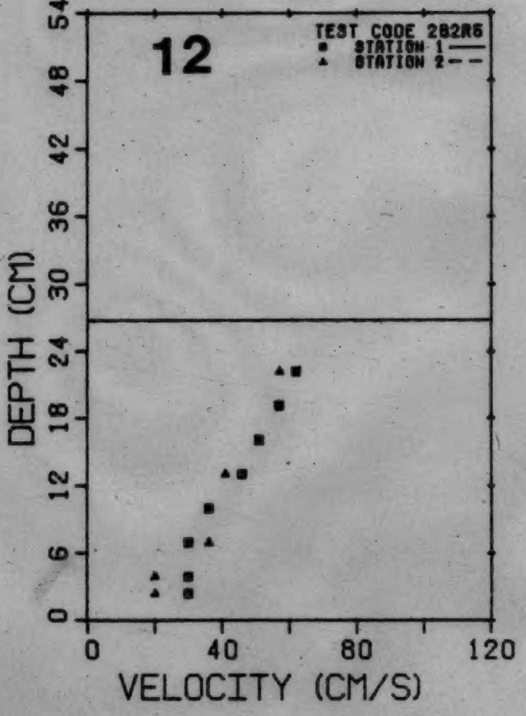

7
TEST CODE 2A4L3
■ STATION 1 ——
▲ STATION 2 – –
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

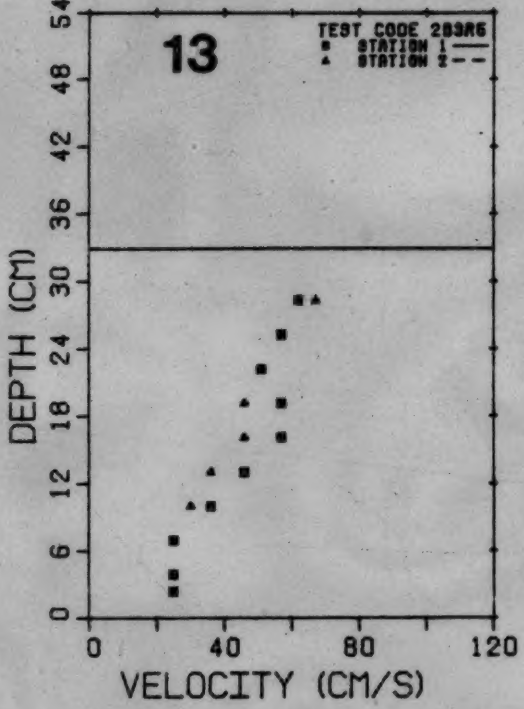

8
TEST CODE 2B2L3
■ STATION 1 ——
▲ STATION 2 – –
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

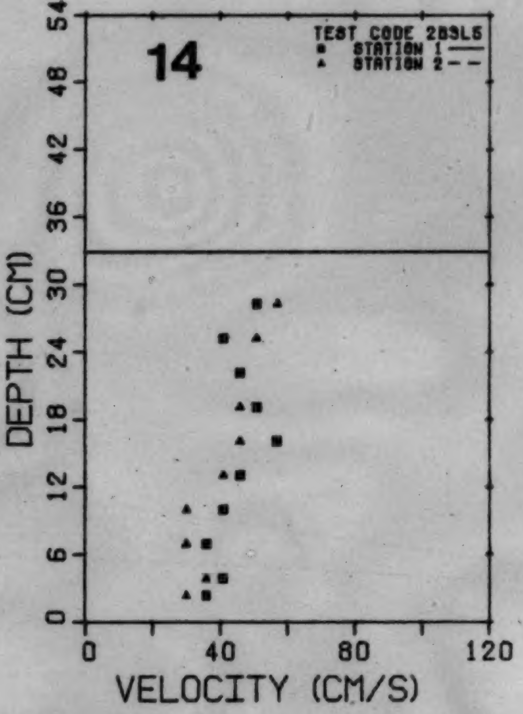

9
TEST CODE 2A4L5
■ STATION 1 ——
▲ STATION 2 - -
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

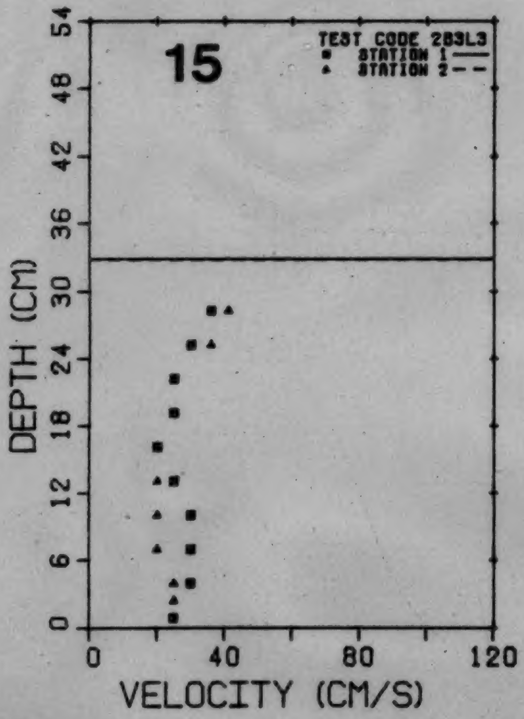

10
TEST CODE 2A4R5
■ STATION 1 ——
▲ STATION 2 - -
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

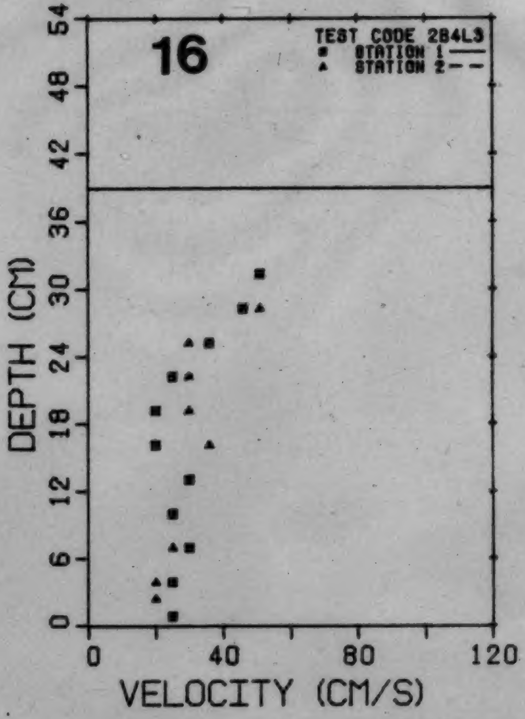

11
TEST CODE 2B2L5
■ STATION 1 ——
▲ STATION 2 - -
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

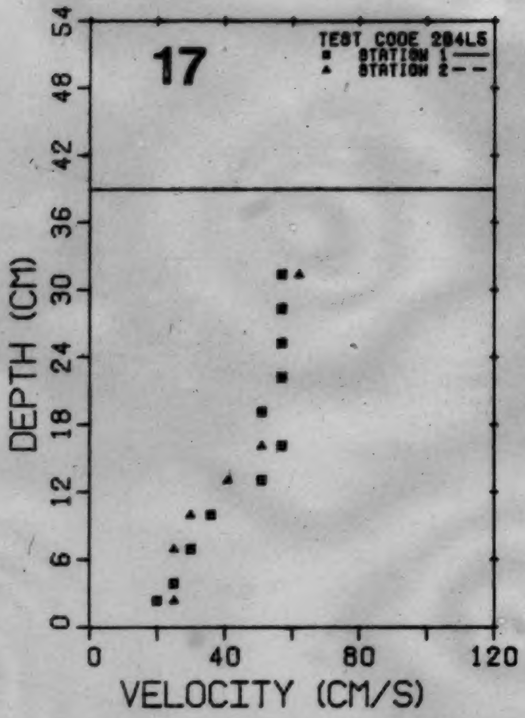

12
TEST CODE 2B2R5
■ STATION 1 ——
▲ STATION 2 - -
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

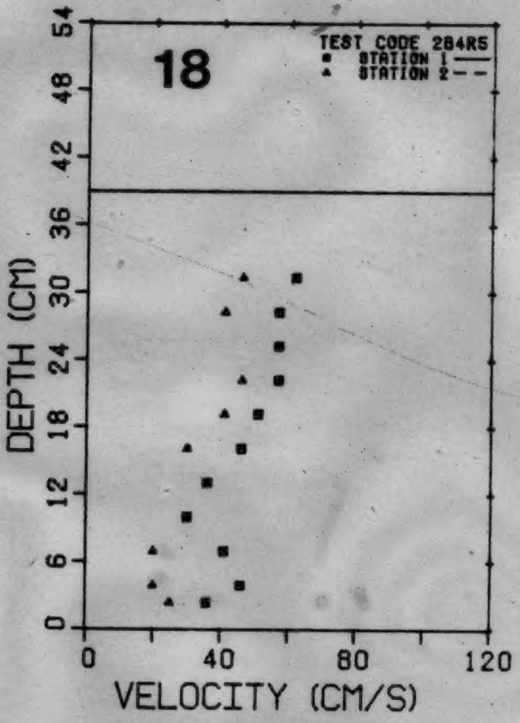

13
TEST CODE 283R6
■ STATION 1 ——
▲ STATION 2 – –
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

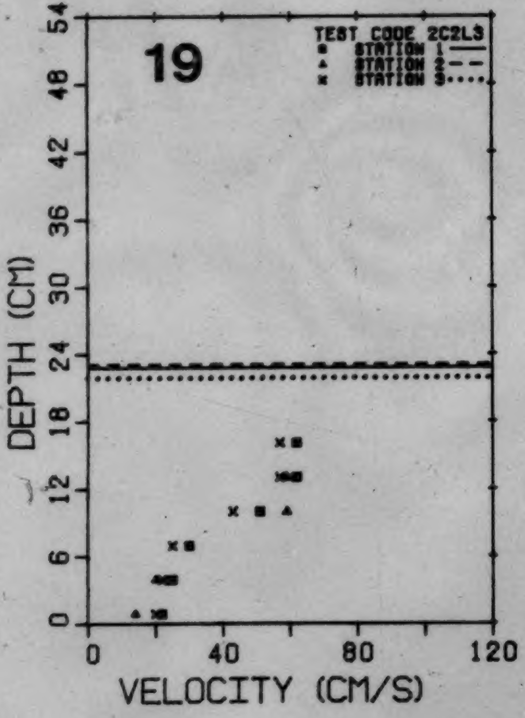

14
TEST CODE 283L6
■ STATION 1 ——
▲ STATION 2 – –
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

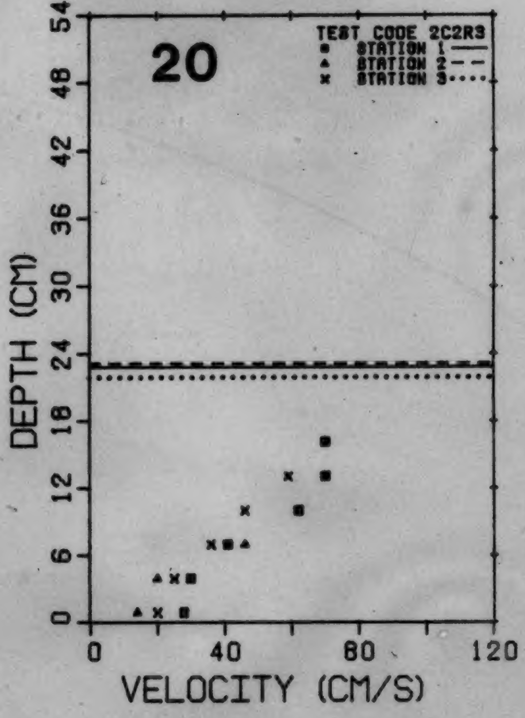

15
TEST CODE 283L3
■ STATION 1 ——
▲ STATION 2 – –
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

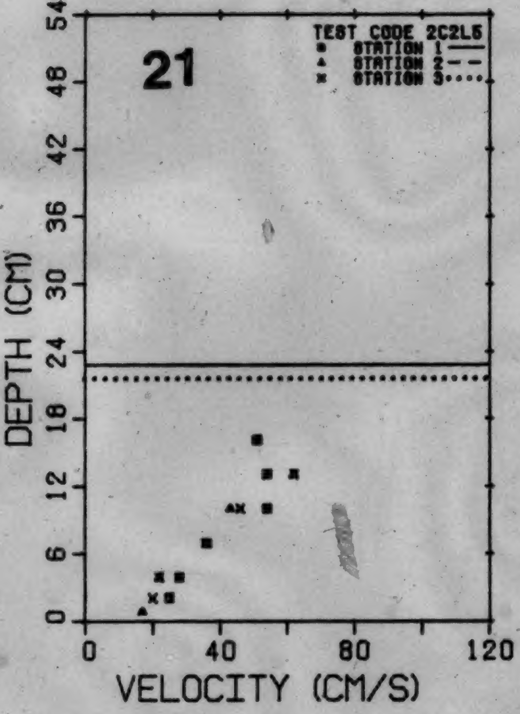

16
TEST CODE 284L3
■ STATION 1 ——
▲ STATION 2 – –
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

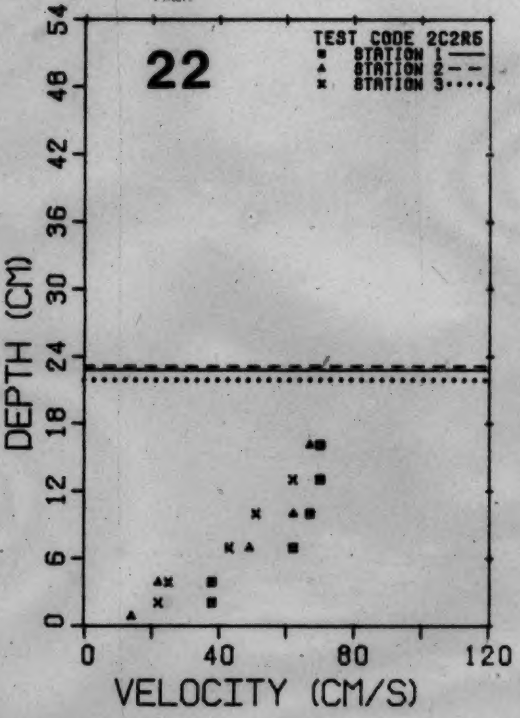

17
TEST CODE 2B4L5
■ STATION 1 ——
▲ STATION 2 - - -
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

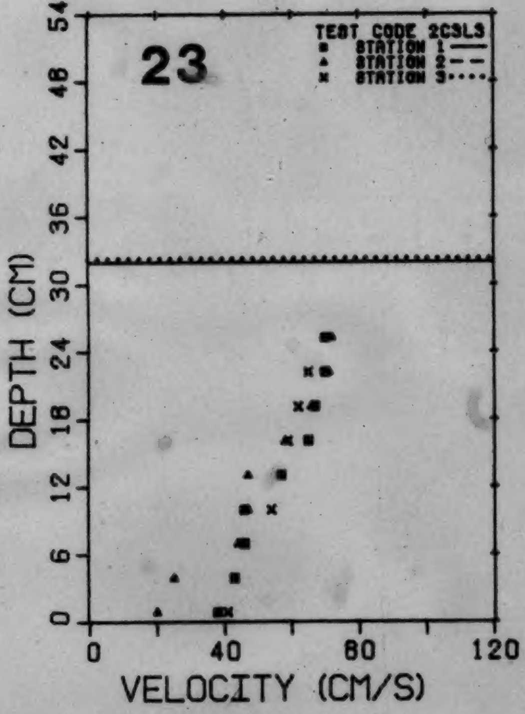

18
TEST CODE 2B4R5
■ STATION 1 ——
▲ STATION 2 - - -
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

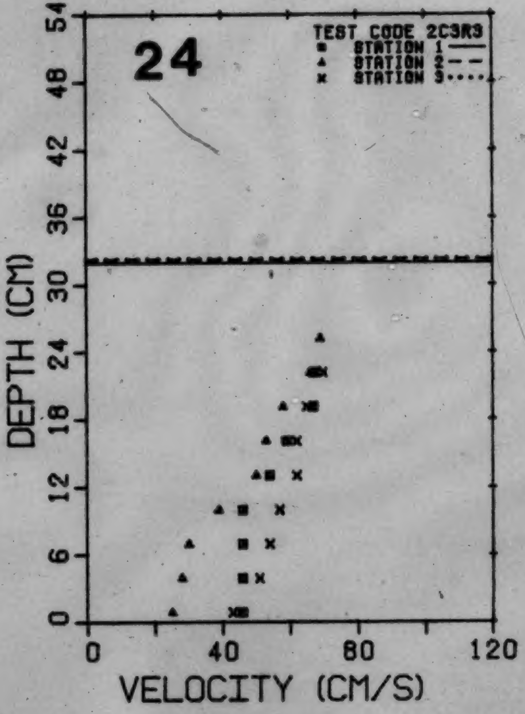

19
TEST CODE 2C2L3
■ STATION 1 ——
▲ STATION 2 - - -
× STATION 3 ·····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

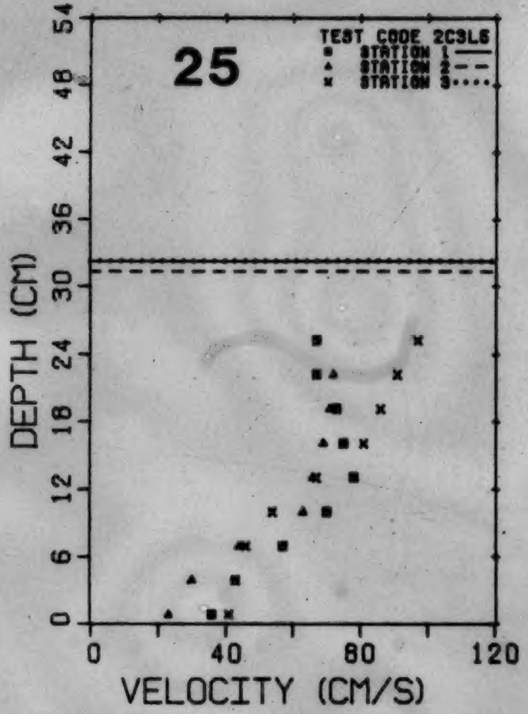

20
TEST CODE 2C2R3
■ STATION 1 ——
▲ STATION 2 - - -
× STATION 3 ·····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

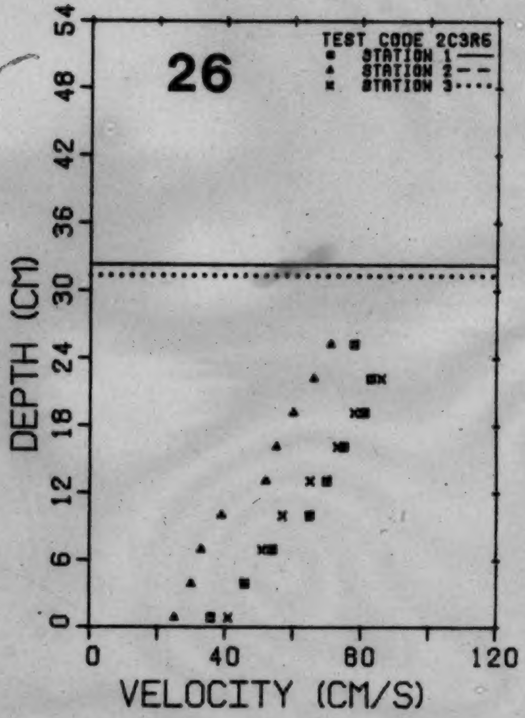

21
TEST CODE 2C2L5
STATION 1
STATION 2
STATION 3
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

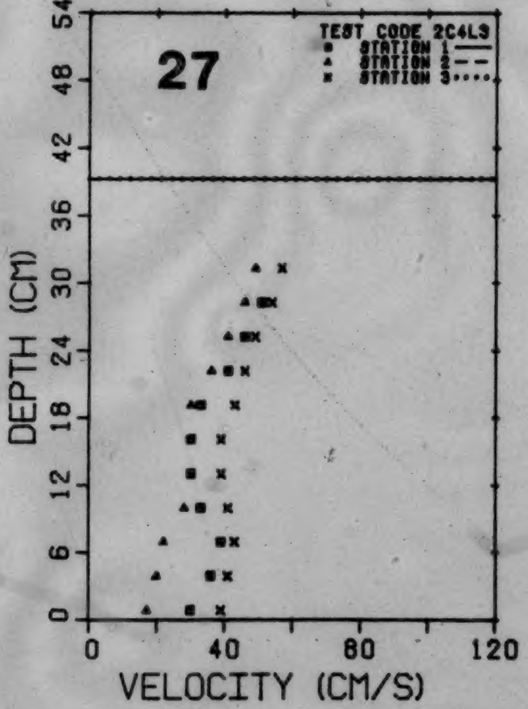

22
TEST CODE 2C2R5
STATION 1
STATION 2
STATION 3
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

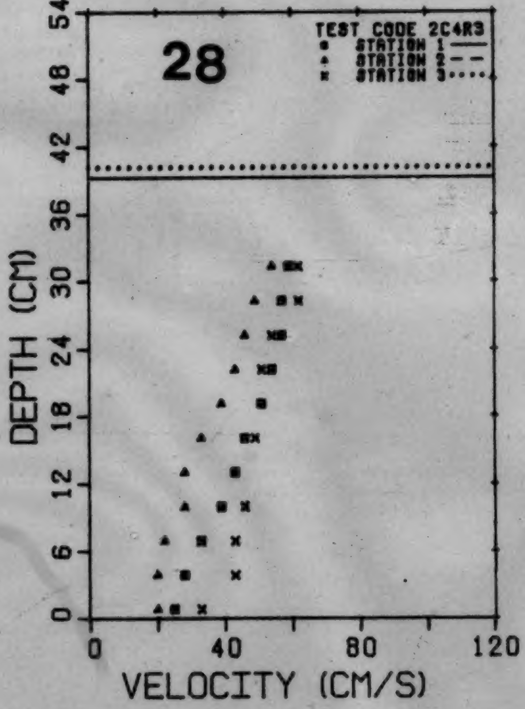

23
TEST CODE 2C3L3
STATION 1
STATION 2
STATION 3
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

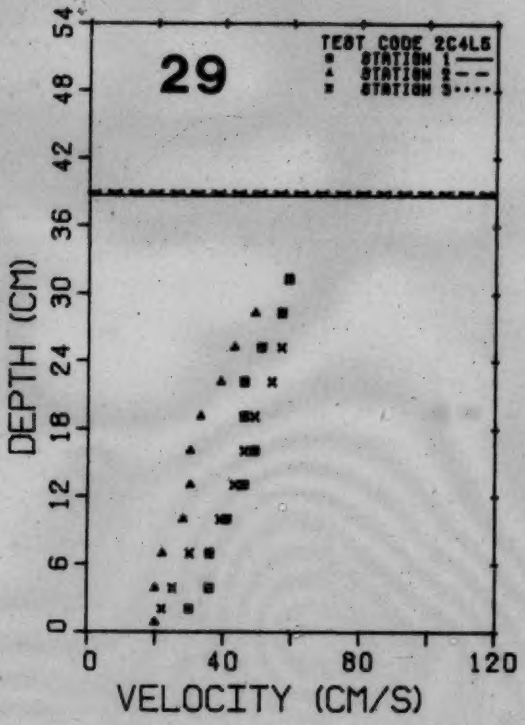

24
TEST CODE 2C3R3
STATION 1
STATION 2
STATION 3
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

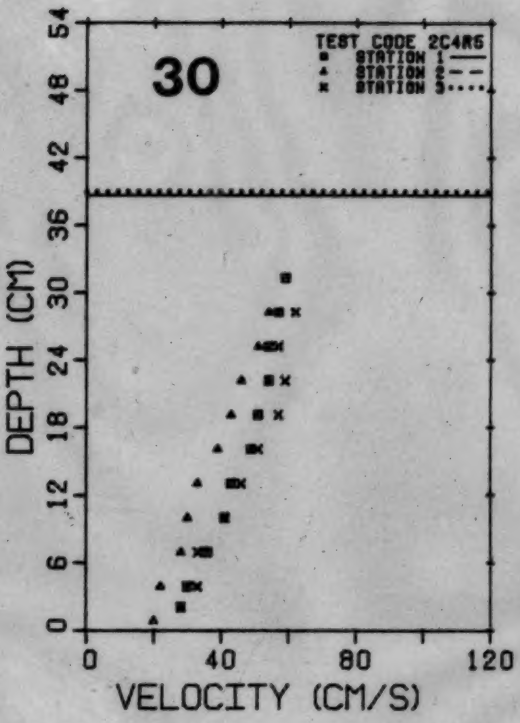

25
TEST CODE 2C3L6
STATION 1
STATION 2
STATION 3
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120


26
TEST CODE 2C3R6
STATION 1
STATION 2
STATION 3
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120


27
TEST CODE 2C4L3
STATION 1
STATION 2
STATION 3
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120


28
TEST CODE 2C4R3
STATION 1
STATION 2
STATION 3
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120


29
TEST CODE 2C4L5
■ STATION 1 ——
▲ STATION 2 – – –
✕ STATION 3 ·····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120


30
TEST CODE 2C4R5
■ STATION 1 ——
▲ STATION 2 – – –
✕ STATION 3 ·····
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

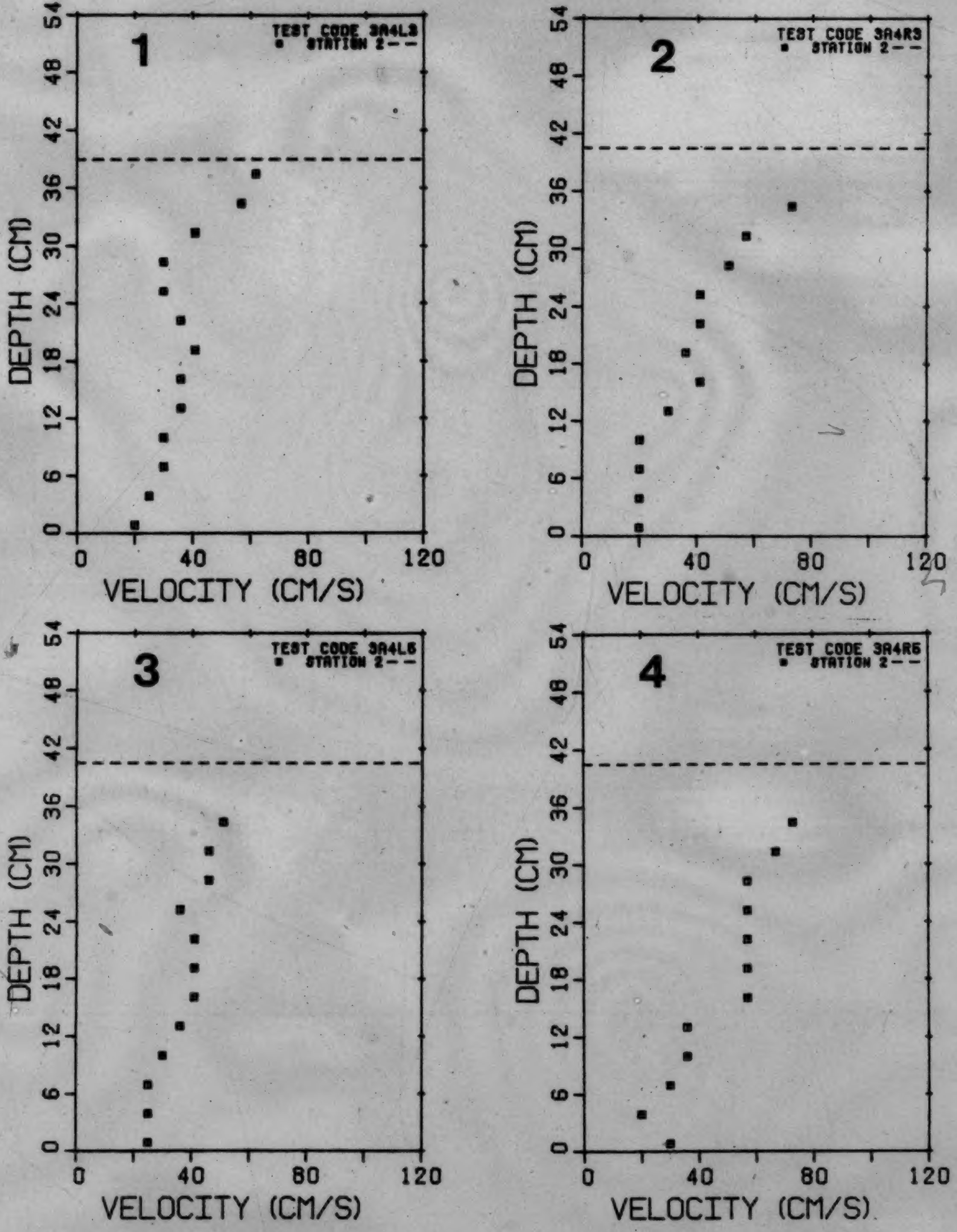
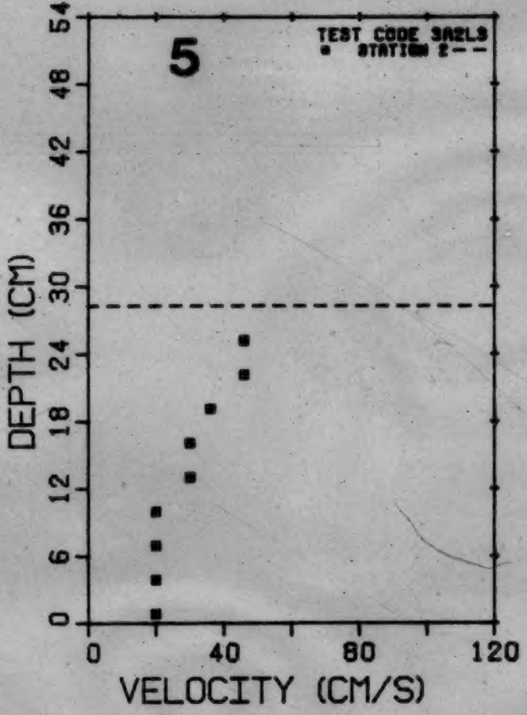
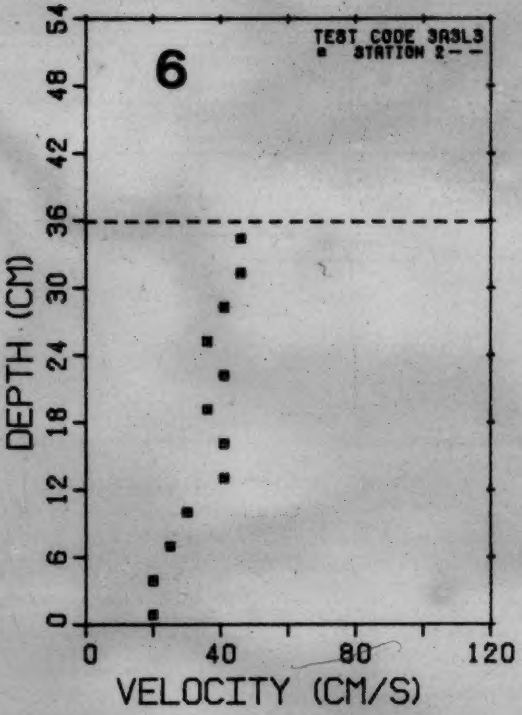
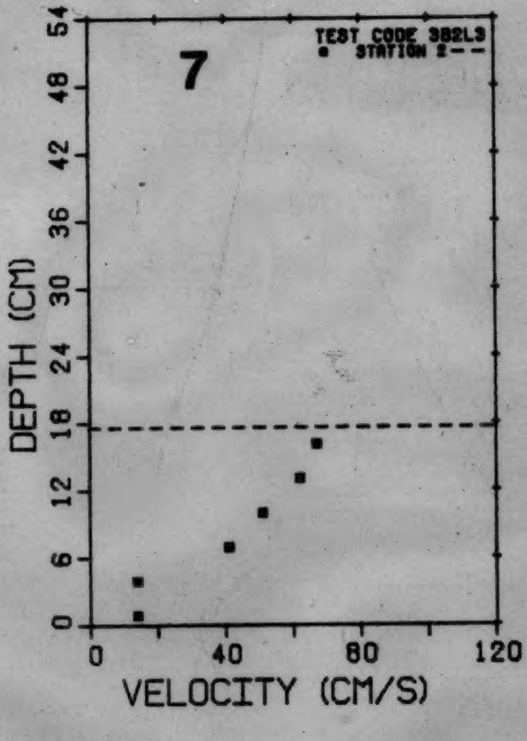
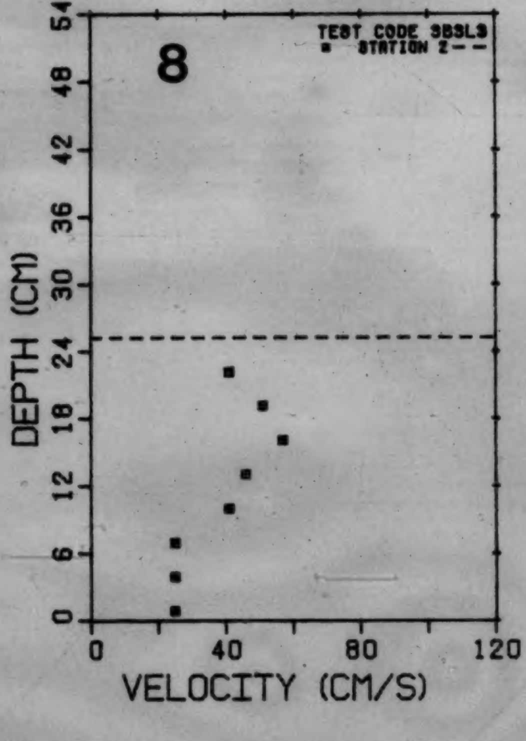


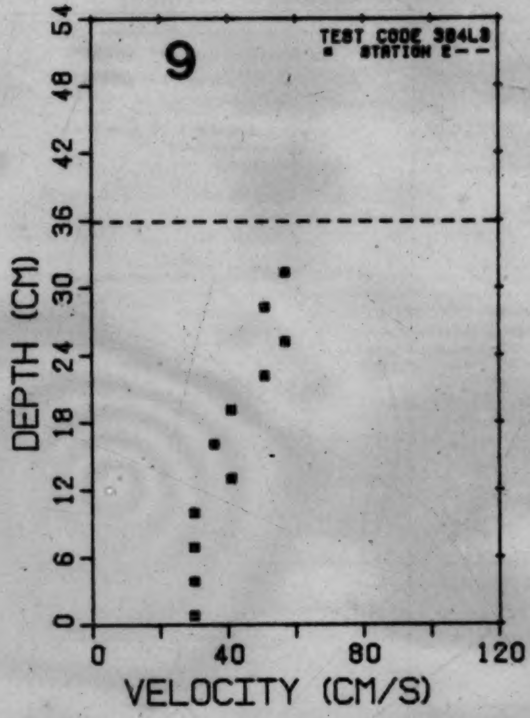
FIG. 1.3. Denil 3: velocity profiles at non-central normals.

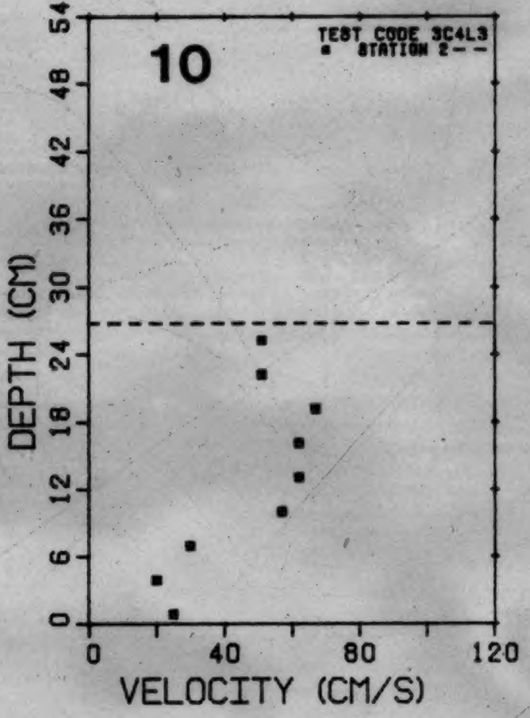

5
TEST CODE 3A2L3
STATION 2
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

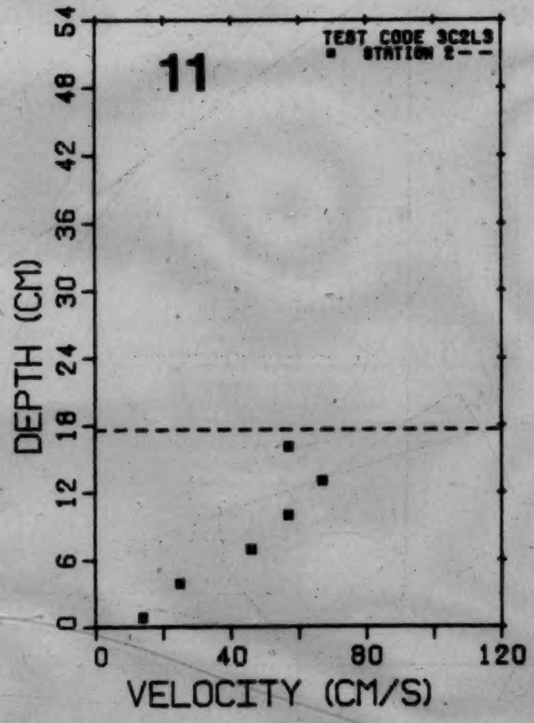

6
TEST CODE 3A3L3
STATION 2
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120

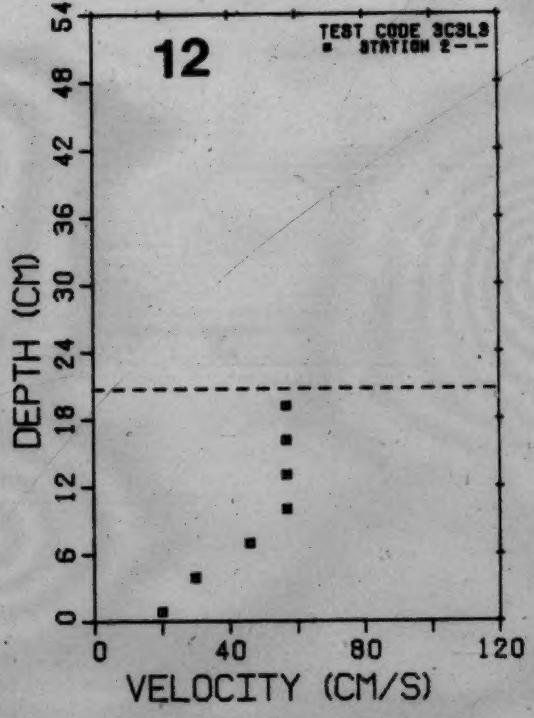

7
TEST CODE 3B2L3
STATION 2
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120


8
TEST CODE 3B3L3
STATION 2
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120


9
TEST CODE 3B4L3
■ STATION 2 - -
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120


10
TEST CODE 3C4L3
■ STATION 2 - -
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120


11
TEST CODE 3C2L3
■ STATION 2 - -
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120


12
TEST CODE 3C3L3
■ STATION 2 - -
DEPTH (CM)
0
6
12
18
24
30
36
42
48
54
VELOCITY (CM/S)
0
40
80
120